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MATHEMATICAL MODELS FOR ECO-INDUSTRIAL NETWORKS

BY

CALLUM R. BISSETT

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF THE

REQUIREMENTS FOR THE DEGREE OF

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IN

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MASTER OF SCIENCE THESIS

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ABSTRACT

Industrial ecology and sustainable development share many principles with industrial and systems engineering. The interdisciplinary qualities and integrated systems approach enables consideration of practical real-world problems. This master's thesis explores the boundaries and linkages between multiple topics and develops quantitative mathematical models to solve two modern problems of sustainability in supply networks.

Two key contributions are made in this thesis. The first summarizes an extensive literature review of industrial ecology and related fields, developing a more inclusive scope to better address sustainable development opportunities in industrial ecosystems. The second proposes mathematical models to solve configuration problems for eco-industrial network design.

The models are used in two scenarios encountered in the literature. Scenario 1 is design of a new planned eco-industrial network from a subset of interested independent firms. Scenario 2 tests the models to maintain the system, and add or remove members of an existing eco-industrial network. The models are shown to demonstrate flexibility to extend to a number of further relevant problems in sustainability.

Significant linkages between research fields are found in the literature, including multiple engineering disciplines and natural sciences, recycling, waste management and several social sciences. The sparse links between industrial ecology and supply chain and reverse logistics are expanded.

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LIST OF SYMBOLS

L	Set of supply nodes and material inputs
M	Set of producer nodes
N	Set of market demand nodes and product outputs
R	Set of recipes. Technological coefficients for transforming inputs into outputs
S_l	Supply capacity of input l
D_n	Demand threshold for product output n
X_{lm}	Amount of input flow of l from supply node to producer m
$Y_{lmm'}$	Amount of input flow of l from producer m to producer m'
$Y_{lm' m}$	Amount of input flow of l from producer m' to producer m
Z_{mn}	Amount of product output flow from producer m to demand node n
r_m	Recipe at producer m
$a_{r,l}$	Technological coefficient for inputs. Amount of input l required in recipe r_m
$b_{r,n}$	Technological coefficient for product outputs. Amount of n produced by recipe r_m
$b_{r,l}$	Technological coefficient for by-product outputs. Amount of l produced by recipe r_m
$h_{r,m}$	Rate of production of recipe r_m

cx_{lm} cost per unit flow from external supplier l to producer node m
 $cy_{lmm'}$ cost per unit flow of l from producer node m to producer node m'
 cz_{mn} cost per unit flow from producer node m to external demand node n
 dx_{lm} distance between supplier l and producer m
 $dy_{mm'}$ distance between producer m and producer m'
 dz_{mn} distance between producer m and market n
 wi_l weighted value of inputs and by-product outputs of type l
 wo_n weighted value of product outputs of type n
 $rm_{r,m}$ binary array corresponding to use of recipe r by producer m
 f objective function for cost
 bpw_l Environmental cost for by-product l waste
 vmt Virgin material scalar cost
 env Total environmental cost.
 emp Positions of employment created
 $jobs_{h_{r,m}}$ Number of employees required at rate of production $h_{r,m}$

CHAPTER 1 – INTRODUCTION

This thesis will provide an extensive review of literature in industrial ecology and contributing disciplines. The review will provide knowledge for developing quantitative models to aid design and assessment of eco-industrial networks. An abbreviated model will be developed and two scenarios tested. This introductory chapter comprises three sections. The first provides an overview of sustainability and justification of the thesis topic. The second outlines objectives and procedures for the literature review. The third section defines the methodological framework for the model.

1.1 Sustainability Overview and Thesis Rationale

Sustainability and sustainable development have progressed from scientific and social movements that warn of environmental crises towards being central values for industry, governments and society.

Sustainability is most commonly defined as “*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*” from the report “Our Common Future”, the Brundtland Commission Report (Brundtland, 1987). Three overlapping circles are universally understood to depict sustainability components as seen in Figure 1. The three main components are economy, environment, and society. Sustainability is the area where all three components converge. The overlap of society and environment considers Eco-social factors. The overlap of society and economy is Socio-economics. The overlap of Economy and the Environment can be considered Eco-economics.

A recurring theme in this thesis is effective use of resources. We have a powerful written history of resource scarcity warnings, and increasing attention to related issues. In "an essay

on the principle of population" in 1798, Thomas Malthus first causally related the growth of population to natural resources and societal wealth. He showed a cycle of economic growth causing population growth, which in turn caused resource depletion, inevitably followed by disease, famine and population decline. Malthus' theory was linked to resources *locally* available, because technology and transportation at the time provided only local access.

Figure 1 - The Classic Factors of Sustainability

The 'Malthusian Trap' is evident for most of human history, until the Industrial Revolution broke the Malthusian limitations. Improved production and transportation technology allowed access to *global* resources, which fueled and fed population growth unchecked.

In 1971 an equation was developed that relates Malthus' theory and the post-industrial revolution society. The IPAT equation links population growth, affluence and technology, to environmental impacts such as resource depletion (Ehrlich & Holdren, 1971) [2]:

$$I = P * A * T \quad (1)$$

This equation assesses environmental impact as the product of simplified factors, where *Environmental Impact = Population * Affluence per capita * Technological enablers*. A summary of trends in these factors highlights a need for change global resource consumption.

Today's world population is slightly over 7 billion, and estimated to exceed 9 billion by 2050, as shown in Figure 2 (US Census Bureau, 2014).

Figure 2 - Global Population Trend 1950-2050 (US Census Bureau, 2014)

The predicted population of 9 billion includes an additional 3 billion middle-class consumers. Production and consumption (Figure 3) are growing even faster than population.

Figure 3 – Global Trends in Gross Domestic Production (GDP), Total Consumption and Household Consumption (The World Bank)

Advances in technology may have broken the Malthusian Trap, but contribute to environmental impact by causing increased use of critical finite resources such as the rare

metals used in electronics and other consumer goods, often not recovered after use (BGS). However, technology can also contribute to solutions through more effective resource use, such as cycling of resources resulting from the planning and implementation of the eco-industrial networks studied in this thesis.

It is easy to comprehend that trends of increasing population, coupled with increasing affluence and consumption lead to an exponential increase in environmental impact, at least according to the IPAT equation.

In 1968, before the IPAT equation was created, “Tragedy of the Commons” warned against overconsumption of shared finite resources in Britain (Hardin, 1968). A group of international leaders and MIT scientists followed the IPAT equation with a deeper assessment of Impact trends, in “limits to growth” (Meadows, Goldsmith, & Meadow, 1972). These publications drew much attention to issues surrounding environmental sustainability. A tipping point for global awareness was the Earth Summit of 1992 in Rio de Janeiro, a global conference of world leaders to address sustainability issues in society, economics and environment. The summit led to formation of the UN Environmental Programme “Agenda 21”, a plan for global sustainable development through economic and social dimensions, with emphasis on resource consumption and ecosystem trends (UNEP, 1992). The Summit led to the creation of several industry, governmental, and non-governmental organizations such as the World Business Council for Sustainable Development (WBCSD), and the UN Development Group and many of its member organizations (UNDG).

The UN sponsored periodic follow-up summits, including The Millennium Summit in Johannesburg 2002, and Rio+20 2012 again in Brazil. The Millennium Summit generated 8 Millennium Development Goals (MDG). Social issues account for the first 6 goals,

environmental sustainability appears only 7th, and economics is not addressed directly (UN). By 2012 however, Rio+20 aimed to address only two issues, “How to build a Green Economy” and “International coordination for sustainable development”. A realization has occurred that collective action through the global economic markets is the most effective path towards sustainability. This positive relationship between economic growth, social benefits and resource conservation has been argued in numerous publications since 1992 (Friedman, 2009) (Hawken, 2010).

This thesis is written in the temporal context of critical global planning agendas towards sustainability. Many of the arguments here gain weight from the recent conferences of the World Economic Forum (WEF) in Davos, Switzerland, and the UN Framework Convention on Climate Change (UNFCCC) in Warsaw, Poland.

These conferences have very different backgrounds and relationships to sustainability. The WEF was founded in the 1970’s as a not-for-profit business management forum (World Economic Forum), preaching “stakeholder” principles of company accountability to “employees, customers, suppliers, governments, civil society and anyone affected by the operations”, not just shareholders. The WEF’s philosophy is economically driven and broadly connected to sustainability. UNFCCC is a UN program started in 1992 after the Earth Summit and convened world government leaders to sign treaties for environmental and social sustainability, chiefly targeting climate change through pollution prevention legislation. The Kyoto Protocol was signed in 1997 and remains its key achievement (UNEP).

The relevance and influence of the two organizations on sustainable development has evolved over time, highlighted by the recent meetings outcomes. The UNFCCC has seen increasing resistance to new legislation and wields decreasing influence over global

sustainable development progress. The disagreements are most often economic in principle, and the legislative path to sustainable development is seen as a “trade-off between economic and environmental success” (Stern & Antholis, 2008). The Warsaw Outcomes from the November 2013 UNFCCC made little significant progress.

In contrast, the WEF has grown tremendously in relevance and influence. Until 1997 global businesses enjoyed huge economic growth. Global leaders accept that this came at expense of natural capital and a linear consumption pattern of Take-Make-Buy-Waste. The 2014 Annual Meeting included top Fortune 1000 industry executives, government officials, NGOs and leading researchers. It launched the WEF to the forefront of sustainability solutions, notably the Ellen MacArthur Foundation (EMF) report titled “Towards the Circular Economy” (Ellen MacArthur Foundation, 2013). The document is a global prescriptive, practical, inclusive, and market driven approach to sustainable development of economies, societies and the natural environment.

These two international organizations exemplify the transition in sustainable development away from top-down governance and punitive legislation, towards facilitated public-private collaboration and cooperation through convergence of economic, environmental, and social principles. The executive summary of the 2014 WEF Annual Meeting summarizes the point,

“...the formal architecture for global governance was not designed for the interdisciplinary challenges and collection action problems of today. As a result, international cooperation has yet to fully enter the information age and capture its associate productivity gains” (World Economic Forum, 2013).

The dominant argument in this thesis is that a similar convergence of principles and progress is necessary in parallel academic fields of research and industry. Where planning and implementation of sustainable development through eco-industrial networks, or what the EMF

calls the Circular Economy, is best achieved at the junction between branches of economics, engineering, social and natural sciences, and operations management research fields.

Several books inspired the design aspect of this thesis, each emphasizing design as root cause and solution to problems of waste and resource use. Books such as Sustainability by Design (Ehrenfeld J. , 2008), Cradle 2 Cradle (McDonough & Braungart, 2002), Design is the Problem (Shedroff, 2009), and The Upcycle (McDonough & Braungart, 2013) explore the principles of design in depth.

Some of the biggest private consumer and industrial product firms in the world have made sustainability a topmost priority for sustainable competitive advantage. Wal-Mart (Humes, 2011), Unilever (Unilever), Renault (Ellen MacArthur Foundation, 2013), Levis (Levi Strauss & Co., 2014), and Philips (van Houten, 2014) are some of the most noteworthy examples from a number of high profile companies making great strides. Each exemplifies improved economic *and* environmental performance through product and supply chain redesign.

1.2 Literature Review Objectives and Procedures

The literature review will consist of two parts. The first focuses on scholarly research articles in the nascent field of industrial ecology. The objective is extensive conveyance of theoretical and practical concepts, applied cases, evolution, and planning paradigms in this topic. This review will reveal a convergence of research directions by broadening the scope of industrial ecology to include literature from several external disciplines. This expanded consideration can aid improvements in operations, planning and implementation of sustainable industrial networks.

The target scholarly material will be identified using a hybrid approach. Qualitative inference will be the predominant method to explore relationships between research themes, with elementary use of quantitative methodologies like citation analysis (Pilkington & Meredith, 2009) and bibliometric analyses (Halvey & Keane, 2007).

The process will begin with basic bibliometric searches for relevant articles using Google Scholar (Google Inc.)¹. The searches will follow an iterative three-step approach of choosing a search term, searching for articles with the term appearing anywhere in the article, then for the term appearing in the article title. The steps will be repeated, generating increasingly relevant and specific search terms while a qualitative knowledge of each field develops. The most heavily cited and most recent articles returned will be surveyed for relevance, and works cited therein. Articles with substantial literature reviews, with abstracts intuitively deemed pertinent will be reviewed. From these sources an appropriate selection will be referenced in the written review. The process will continue until a thorough investigation of industrial ecology literature has been composed, and the convergence of research in related external fields is conveyed.

1.3 Modeling Methodology

The objective is to develop a quantitative model that aids planning and management of eco-industrial networks. The process begins with the formulation of scenarios, followed by a summary of modeling approaches in industrial ecology and those focusing on network modeling problems with sustainability considerations.

- Scenario One – No coordinated network yet exists
- Scenario Two – An industrial or eco-industrial network already exists.

¹ The flawed nature of Google Scholar bibliometric analysis is recognized (Arizona State University Libraries), but it is useful nonetheless for generally highlighting the relative importance of terms and concepts within fields of study

Problem Formulation

A problem statement for each scenario must be formulated. The most basic representation of the scenarios will be posed to develop the simplest models that address the problem. The reduction of complexity aims to speed model development. The scope of the problem statements can be narrowed by introduction of assumptions that generate initial conditions and information necessary for model development and solution.

Assumptions

The assumptions will be based on standard conditions observed in the literature, and cover the initial conditions, information availability, and firms' pre-requisite feasibility testing stages.

Model Formulation and Solution

A basic quantitative model framework will be developed and tested for feasibility. All models developed will be solved using CPLEX, through the General Algebraic Modeling System (GAMS) software for quantitative examples of the model (GAMS Development Corp.). The basic model will follow an iterative process of development, test in GAMS, and analysis of feasibility in solving the problems 1 and 2. Once a feasible model has been developed, the data will be adjusted to reflect problem one, then tested to solve it. The iterative process will again be followed until problem two has been solved. The model will then be extended to consider several special cases each with additional real-world sensitivities evident in the literature review.

Analysis

The results of the GAMS solutions will be systematically analyzed and the models' ability to solve the two problems will be accepted or rejected. The flexibility of the model and its potential utility in eco-industrial network planning and management will be discussed.

CHAPTER 2 – INDUSTRIAL ECOLOGY LITERATURE REVIEW

This chapter reviews the knowledge and progress of several interdisciplinary and interconnected fields in the context of industrial ecology. It will illustrate the convergence of these different fields and their approaches to planning and implementing sustainable industrial systems. Through the research in this thesis it has become apparent that academia struggles to find consensus on nomenclature and boundaries for studying aspects of sustainability across a diverse range of loosely linked fields; a point defended by Allenby in his ontological discussion of industrial ecology (Allenby B. , 2006). Selected sources provide conceptual clarity and development within the assorted fields, and inspire, support or challenge our approach to modeling eco-industrial systems. It will not provide a comprehensive review of each independent field. This review will draw frequently upon sources such as McKinsey & Company reports for an economic and private industry viewpoint, with the aim of supporting the trends and conclusions highlighted from the scholarly literature.

2.1 Identification and Classification of Scholarly Articles

At the time of writing this thesis, a simple Google Scholar search for scholarly articles containing the exact phrase “industrial ecology”, or “industrial symbiosis” returned 17,200 results. A search for either phrase in the title of articles returned 2,050.

Categorization of articles was challenging. Industrial Ecology and the related literature are broad fields and relatively immature. The majority of highly referenced articles were published after 1990. The most cited articles were addressed first to gain an understanding of the concepts, before categorizing the articles by type. Each article reviewed offers one or more of three summary objectives.

Table 1 - Summary of Industrial Ecology Literature Objectives

3 Summary Objectives
Develop concepts, definitions, or classifications of industrial ecosystems
Discover, examine, or compare cases of implemented industrial ecology
Determine conditions, methodologies, or frameworks that may assist in planning or facilitating industrial ecosystems.

2.2 Conceptual Overview, Ecology & Industrial Ecology, Biomimicry

The basic motivation to systemically improve human activities is drawn from parallels in ecological systems, and is the rationale for the industrial ecology studies reviewed. The articles, books, and publications citing case examples all appear to share the basic assumption that there is untapped value to be gained through industrial ecosystem concepts. All authors also appear to agree that conceptually, Industrial Ecology can contribute to making human activities less environmentally harmful, more socially beneficial, and also profitable. The breadth of this statement symbolizes the diversity of definitions, research, opinion, analysis, assumptions, and frameworks in the Industrial Ecology literature.

Ecology

Networks are formed in nature based on symbiotic relationships. The study of which is titled “Ecology”, defined by the Merriam-Webster dictionary as, “a branch of science concerned with the inter-relationships of organisms and their environments.”

According to Allenby, natural ecosystems are at first inefficient systems that consume unlimited amount of resources and create unlimited amounts of waste. As ecosystems mature,

the components of the system reuse increasing amounts of resources in cycles, and release decreasing amounts of waste from the system. Ultimately mature systems create no waste, and require only energy as an input to drive the system. As seen in Figure 4.

Figure 4 - Three Types of Ecology based on (Allenby B. R., 1992)

Industrial Ecology

It can be argued that human commercial activity also occurs in networks, commonly referred to as Industrial Ecology or “IE”. The word ‘industry’ in industrial ecology has numerous connotations. In this thesis we assume the most encompassing of meanings offered, where industry refers to the “sum total of human activity” (Graedel & Allenby, 2010). To define the oxymoronic term of Industrial Ecology, a synthesis of reviewed descriptions creates a wordy definition of Industrial Ecology:

An holistic, interdisciplinary systemic approach to optimizing human commercial activity, principally the flows of substances and energy, through effective design inspired by nature’s ecological processes, where success is defined by continuous economic, environmental, and social enhancement.

Numerous definitions are offered in the literature for the field of industrial ecology. Early definitions were simple. The early industrial ecology pioneer, Jesse Ausubel, stated the goal for industrial ecology “*is a more elegant, less wasteful network of industrial processes*” (Ausubel, 1994).

Industrial Ecology is relatively new compared to other sciences but has been developing at an accelerating rate (Yu, Davis, & Dijkema, 2013). Industrial Ecology and its synonymous practice of Industrial Symbiosis was considered by one international group of collaborating researchers to have metastasized to scientific maturity.

IE/IS has “...graduated from academic curiosity to practical tool supported by policy makers, business organizations and environmental NGOs alike – to address a broad policy agenda encompassing innovation, green growth and economic development in addition to the traditional focus on resource efficiency.” (Lombardi, Lyons, Shi, & Agarwal, 2012).

Although the expression “industrial ecology” appeared in publications much earlier (Erkman, 1997), it was in 1989 that Robert Frosch and Nicholas Gallopoulos made the first

notable comparison of industrial systems to non-human ecological systems in the heavily cited article “Strategies for Manufacturing” in the Scientific American (Frosch & Gallopoulos, 1989). The leading caption of this article summarizes a key tenet for Industrial Ecology and the main sense gained from the reference to nature, *“Wastes from one industrial process can serve as the raw materials for another, thereby reducing the impact of industry on the environment”*.

Frosch and Gallopoulos deliver a volley of statistics on resource scarcity and pollution. The authors summarize traditional industrial models as individual manufacturing processes that take in raw materials and generate products to be sold, plus waste. They posit a transformation to a “more integrated model: an industrial ecosystem”. Where,

“the consumption of energy and materials is optimized, waste generation is minimized and the effluents of one process-whether they are spent catalysts from petroleum refining, fly and bottom ash from electric-power generation or discarded plastic containers from consumer products-serve as the raw material for another process.” (Frosch & Gallopoulos, 1989)

The article describes industrial ecosystems as analogous to biological ecosystems; where biological systems are a process in which plants synthesize nutrients that feed herbivores, in turn feeding a chain of carnivores whose wastes and bodies eventually feed further generations of plants.

The article was pioneering and recognized that an ideal industrial ecosystem *may never be attained in practice*, but both *manufacturers and consumers must change their habits* to approach it more closely if the industrialized world is to maintain its standard of living, and the *“developing nations are to raise theirs to a similar level without adversely affecting the environment.”* They propose that if both industrialized and developing nations embrace

changes, it will be possible to develop a more closed industrial ecosystem in the face of *”decreasing supplies of raw materials and increasing problems of waste and pollution.”*

Frosch and Gallopoulos succinctly capture many of the motivations for society and industry to embrace industrial ecology. They also present many of the most significant challenges of planning and implementing industrial ecology in practice. Most of the challenges still go unresolved, despite the exponential rise of professionals, academics and other actors devoted to industrial ecology and industrial symbiosis since this article was published. The paper also uses phrases that are now buzzwords in reverse logistics, waste management, recycling, and supply chain management.

The Frosch and Gallopoulos article began a major movement (Erkman, 1997). By 1991 a conference Washington DC at the National Academy of Sciences had been held under the title “Industrial Ecology”. The resulting proceedings set the early concepts for industrial ecology, and the initial vocabulary and directions for academics, industrialists and policymakers to approach application (Jelinski, Graedel, Laudise, McCall, & Patel, 1992). The systemic models of Frosch and Gallopoulos remain the foundational paradigms of industrial ecology.

The figure 5 illustrates three types of industrial ecosystems with similar structure to Allenby’s three types of ecosystems in Figure 4. Immature industrial systems consume large amounts of natural resources and create large amounts of waste, and products to meet societies market needs. At the lowest maturity these products are discarded as waste to the natural environment after their useful life. As maturity increases more materials are cycled between industrial actors, and less waste is created by society. Fully mature industrial ecosystems in this model form networks where no harmful waste is released back to the environment, and all end-of-life products are recovered and reused to create new products.

The bottom section of figure 5 shows the level of materials in the natural environment. Immature ecosystems cause levels of unusable waste to build up, and natural resources to be depleted. Type 3 industrial ecosystems allow replenishment of natural resources and creation of no waste. This is the aspirational goal of industrial ecology.

Figure 5 - Three Types of Industrial Ecosystem By Maturity and Time (Author defined)

"Industrial Ecology, like the biological system...rejects the concept of waste...wastes are merely residues that our economy has not yet learned to use efficiently" (Graedel & Allenby, 2010)

IE Analogy – Phrasing & Feasibility

The literal analogy of ecology versus industrial ecology has been examined closely for its feasibility (Ehrenfeld J. , 2004), both as an ideal and in functioning systems (Cote & Hall, 1995) (Lowe & Evans, 1995) (Chen, Wang, Yang, & Shi, 2010). Frosch and Gallopoulos are most frequently quoted for originating the concept of industrial ecology but materials scientist, Robert Ayres also receives credit for the ecological analogy under the term Industrial Metabolism (Ayres R. U., 1989). In the majority of literature examined, industrial ecology has been the preferred term over industrial metabolism, which has been used as a metric of sorts for industrial ecosystems. Ayres defined it as *"the whole integrated collection of physical processes that convert raw materials and energy, plus labour, into finished products and wastes..."* (Ayres R. , 1994)

Early publications study similarities and differences between the two separate but comparable systems of nature and industry. There is also emphasis on the necessity to enhance and employ the concept (Allenby B. R., 1992) (Jelinski, Graedel, Laudise, McCall, & Patel, 1992). They seek acceptance or rejection of the industrial ecology analogy and the field's scientific legitimacy. Ecological and industrial systems were seen in this period as separate, independent sets of systems. Latterly, controversy over the analogy has diminished but disagreement remains in studies on the parallels between flows and processes of natural versus industrial systems (Ehrenfeld J. , 2004). There is a progression in the theory of discrete ecological and industrial systems, to an acceptance of their connectedness. The natural ecosystem encompasses all activity, and society is part of that ecosystem so everything they create is also implicitly encompassed, including the technosphere (Desjardins, 2013). This

argument implies the possibility of integrating the systems. “Technosphere” and “Biosphere” are classification terms referenced throughout the literature and provide context for natural or industrial ecosystems, and the materials cycled through them (McDonough & Braungart, 2002). The biology and ecology centric viewpoint offers only a vague framework, and is criticized for anti-industry sentiment, but can motivate designs allowing society to exist within the material constraints of the planet.

Levine published a detailed study comparing ecological systems and industrial systems (Levine, 2003). He questions the appeal of modeling industry after nature. He admits many commonalities exist between the concepts, but argues that production of products and the related economic exchanges and transactions differentiate industrial systems beyond the metaphor. The main difference is production terminology. Ecological systems are “push” systems driven by supply, where respiration energy is the input variable, whereas industrial systems are typically “pull” systems driven by demand for products and services. The feedback loops of each system are unique, and different forces drive the actors’ behavior in each system. Industrial actors compete for market share (demand for final outputs) but ecological actors compete for input resources. The second difference Levine outlines is the concept of added value in industrial systems, which is absent in nature. All objects and organisms in nature consist of a small number of simple materials (cellulose, sugars, lipids and proteins). In industrial ecosystems the products created have highest value placed on their immediate purpose, and new materials are created that don’t exist in nature. Combinations and transformations designed to create a “more valuable product”, often result in materials that are useless for any other industrial process or product, and that cannot be returned safely to the biosphere.

In 2003 Robert Ayres further explored the insufficiency of the analogy, adding two more dissimilarities (Ayres R. U., 2004). The first is the absence of a single primary producer in industry. The ecological system has the single input, energy in the form of sunlight, which is harvested into the system by photosynthesizers. On the other hand industry requires multiple inputs including labor, natural resources and capital. The other difference is the evolutionary process. In nature, the Darwinian survival of the fittest (or best reproducer) and the mutation of genes drives evolution. In industry progress is made through innovation, discovery and competition in businesses and society.

A 2009 compared industrial symbiotic processes against the equivalent ecological relationships in natural systems (Liwarska-Bizukojc, Bizukojc, Marcinkowski, & Doniec, 2009). The authors assessed the interactions between actors in ecological terms, and found many similarities the behaviors of the two systems, supporting the legitimacy of the analogy.

Biomimicry

The design implications of the industrial ecology metaphor have been taken literally with instances of incredible success. Biomimicry is a more literal term with similar roots in ecology and aim of advancing technological design. Biomimicry infers that 3.8 Billion years of ecosystem evolution provides expert design blueprints and inspiration (Benyus, 2002). Benyus examines future challenges that face society and the environment, and offers prescriptive solutions based on natural systems. She proposes and reviews nature-inspired advancements for system and product designs in farming, healthcare, Information Systems, Energy and Industry. One chapter relates commerce to redwood forests' endless "closed-loop" flows of materials, nutrients and energy. This is another ecological example that reinforces this thesis, that modeling industrial symbiosis is both possible and necessary. Janine Benyus also founded

the Biomimicry Institute in 2006, aimed at research, education and consulting using these principles and methodologies (Biomimicry 3.8).

Table 2 - Three Key Tenets of Benyus' Biomimicry

Biomimicry Tenets
Nature as model: Study nature's models and emulate these forms, processes, systems, and strategies to solve human problems.
Nature as measure: Use an ecological standard to judge the sustainability of our innovations.
Nature as mentor: View and value nature not based on what we can extract from the natural world, but what we can learn from it.

Introduction of Industrial Symbiosis

The most referenced application of industrial Ecology is Industrial Symbiosis (IS). A subset of industrial ecology, industrial symbiosis denotes the symbiotic relationships between industrial actors that exchange materials, water, energy and often expertise for their mutual economic advantage, and frequently for environmental and social advantages. The term may be used interchangeably with the Industrial Ecology. However, the scope and boundaries of industrial ecology are less restricted.

In the Journal of Industrial Ecology, Marian Chertow offered the most widely accepted definition for Industrial Symbiosis in 2000, which became the anchor definition for the next decade. Chertow describes industrial symbiosis as engaging,

“...traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water and by-products.” (Chertow M. R., 2000).

Rachel Lombardi and Peter Laybourn revised the expression in the same journal in 2012,

“IS engages diverse organizations in a network to foster eco-innovation and long-term culture change. Creating and sharing knowledge through the network yields mutually profitable transactions for novel sourcing of required inputs and value-added destinations for non-product outputs, as well as improved business and technical processes.” (Lombardi & Laybourn, 2012)

Lombardi and colleagues “unpack” and digest each portion of both their definition and Chertow’s. They chart an interesting review of intermediate definition attempts and track the inclusion, exclusion and replacement of the words that lead to their chosen definition.

The most recent literature review of this field was conducted Yu et.al (Yu, Davis, & Dijkema, 2013). They reveal two eras in language of industrial ecology and industrial symbiosis literature. Yu and his colleagues compiled an extensive and insightful bibliometric and network analysis of all research publications that include the terms “Industrial Ecology”, “Industrial Symbiosis”, and “Eco-Industrial Park” from 1997 to 2012. They classify the first era as 1997-2005 and second from 2006-2012. The first was dominated by the consolidation and development of vernacular, discussed earlier in this chapter. The most referenced terms were Life Cycle Analysis, Material Flow Analysis, Industrial Ecology, “environmental impact”, ‘recycling’, ‘ecology’, ‘practical EIP projects’ and ‘principles of IE and sustainable development’. Between 2006 and 2012 they assess the previous era’s keywords to have contributed to the diversity of post-2005 research themes. The variety of terminologies were absorbed into the improved definition of Industrial Symbiosis within the overarching field of Industrial Ecology (Lombardi & Laybourn, 2012).

INDUSTRIAL SYMBIOSIS & INDUSTRIAL ECOLOGY DEFINITIONS

Table 3 - Two Fields Defined: Industrial Ecology vs. Industrial Symbiosis

Industrial Ecology Definitions	
“The science of sustainability” (Graedel & Allenby, 2010)	
“Defined briefly as the means by which our species can deliberately and rationally approach and maintain a desirable global carrying capacity. It is deliberate and rational in contrast to unplanned, precipitous approaches such as famine or disease... Industrial ecology relies on a systems-oriented approach to integration of human economic activity and material management into fundamental biological, chemical, and physical global system.” (Braden R. Allenby, A T&T)	
As defined by Tibbs, industrial ecology 'involved designing industrial infrastructures as if they were a series of inter-locking man-made ecosystems interfacing with the natural global ecosystem' (Tibbs, H.C., 1992)	
“IE takes a systems rather than firm-oriented view to eco- efficiency, with the expectation that this will increase the possibilities for eco-efficiencies at the system, or regional, scale.” (Deutz & Gibbs, 2008)	
Industrial Symbiosis Definitions	
Engaging, “traditionally separate industries in a collective approach to competitive advantage involving physical exchange of materials, energy, water, and by-products. The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity” (Chertow M. R., 2000)	
“Establishment of close working agreements between normally unrelated industrial (or other) organizations that lead to resource efficiency” (Jensen, Basson, Hellawell, Bailey, & Leach, 2011)	

It is logical to expedite agreement on standard designs for Industrial Symbiosis as one contributing factor toward sustainable development (Chertow M. R., 2007). Progress is being made but as evidenced above, agreement on semantics in this field has proven tricky to reach. A small number of journals contribute significantly in industrial ecology research. The two highest contributors are the Journal of Industrial Ecology, published through the Yale School of Forestry and Environmental Studies, and the Journal of Cleaner Production, an international publication with a focus on industrial sustainability. The other four found by Yu et.al to be in

the top six are, Progress in Industrial Ecology, Resources Conservation and Recycling, Business Strategy and the Environment, and Computer Aided Chemical Engineering (Yu, Davis, & Dijkema, 2013). Those involved in editing, publishing, and contributing to these journals deserve tremendous credit for guiding the discussion, and driving the advancement of research in industrial ecology and industrial symbiosis. The Yu et.al bibliometric analysis illustrates the connections between related articles published in different fields of research (Figure 6). Through a close review of the research unearthed by their keyword search, the connection made between disciplines in this thesis is not mirrored in their analysis. Supply Chain, Networks, Reverse Logistics, Recycling and associated risk do not appear in the major areas highlighted in Figure 6. The authors recognize that their review could be narrowed by the limited search terms used, and the limited cross-disciplinary citations in the returned articles.

Peer reviewed journal articles written by academics and practitioners are referenced most in this thesis. As outlined in the introduction, local and national governments, industries, economic and political bodies, and non-governmental organizations have also bought into the promise of industrial ecology and contribute to its advancement and application. Many attempts have been made to employ industrial ecology on various scales, through numerous planning techniques and with inconsistent success (Tudor, Adam, & Bates, 2007) (Gibbs & Deutz, 2007). Examples of industrial symbioses exist on six continents (Lombardi, Lyons, Shi, & Agarwal, 2012).

Figure 6 - Position of Industrial Ecology Within Research Clusters (Yu, Davis, & Dijkema, 2013)

2.3 Industrial Ecosystem Projects - Defined and Assessed

Methods for measurement are required to scientifically quantify and qualify industrial ecology applications. Measurement and metrics is another area of significant ambiguity in the literature. Related discussions surround the correct methodology and metrics for measuring the impacts, potential, and success of industrial ecology (Chiu & Yong, 2004) (Boons, Spekkink, & Mouzakitis, 2011) (Ehrenfeld J. R., 2003). The grand topic of sustainability has a

numerous indicators and metrics (Wilson, Tyedmers, & Pelot, 2007). It is commonly recognized that simple, easily grasped, but accurate metrics are the ones that percolate from industry circles to society at large. The problem with regards to sustainability is that the size, scope and complexity of the problems defy simple summarization without loss of accuracy. The consequence is often misleading abbreviations of reality that undermine the complexity or severity of the issues. The path to solution might be undermined if poor information gains command of public opinion, mainstream media, and policymakers.

Two significant factors contribute to the difficulty in reaching consensus on industrial ecology assessment. The first contributing factor cited is the immaturity of the science, as well as differing levels of experience in contributing fields. Sustainability measurement lacks significant sample sizes when human history is viewed in the context of the Earth's environmental history. Large sample sizes would decrease the contribution of error in statistical analyses, providing more reliable results for environmental decision making. In addition to short recorded history, sample sizes are decreased further by the rapid advancement of technological capabilities. These developments create opportunities and challenges for comparative analysis because equivalent historic data may not be available for new technologies (Korhonen & Snakin, 2005). Some standardized methods of quantitative analysis used for environmental impact evaluation of industrial ecology cases is summarized in this section. The Millenium Development Goals attempted to create better national accounts databases to represent environmentally significant material flows, but consensus and implementation have had limited success in governments (Bartelmus & Vesper, 2000).

Among the most data intensive methods of analysis are Life Cycle Management (LCM) techniques. These tools most commonly include Life Cycle Analysis (LCA), Social Life Cycle Analysis (S-LCA) and Economic Input-Output Life Cycle Analysis (EIO-LCA). There are

abbreviated versions of these analyses that use data inputs for generic processes, but these may not reflect the environmental benefits of processes in industrial ecology.

Life Cycle Assessment is defined by ISO 14000:2009 standards as “*a tool for identifying and evaluating the environmental impact aspects of products and services from the cradle to the grave, from the extraction of resource inputs to the eventual disposal of the product or its waste.*” (International Organization for Standardization Central Secretariat, 2009). A more explanatory definition of LCA is offered by Linnanen et.al.,

‘Life cycle management consists of three views: (1) the management view – integrating environmental issues into the decision making of the company; (2) the engineering view – optimising the environmental impact caused by the product during its life cycle; and (3) the leadership view – creating a new organisational culture.’ (Linnanen et al., 1995)

Criticisms of LCA approaches are many. These vary from a criticism of the time-intensive data requirements, to a complaint that there is not enough detailed accounting for some environmental factors. One critical consideration of all LCA approaches states,

“LCA-based ideas and tools can be viewed as emerging institutional logics of their own. While LCA makes use of many scientific models and principles, it is more a form of accounting than an empirical, observational science. Thus, the life cycle approach implies a kind of ‘social planner’s view’ on environmental issues, rather than the minimisation of a company’s direct environmental liabilities.” (Heiskanen, 2002).

The modeling in this thesis will not account for Life Cycle Analysis, although the expectation is that LCA results of empirical cases using the model would yield significant positive results. Analyses such as material flow analysis (MFA, also known as substance flow analysis - SFA) are also not used in the simple model proposed for this thesis. Such analyses are data intensive, requiring deep knowledge of existing processes, and are not appropriate at the high level of planning that this thesis considers.

The need for detailed data creates problems when new designs are being created. The measurement process of LCA impact analysis becomes a *best guess*, which requires large time commitments and may lead to unreliable results. Both are problematic in a global economy where agility and rapid development play an increasingly vital role. The biggest issue is caused by regulations that hinge on LCA results.

Input-Output analyses face similar challenges. Input-output analyses work very well to capture high-level network interdependencies for materials and resources between sectors, but the aggregation of data does not allow detailed analysis of individual flows. A more complete version of the input-output model for assessment for Industrial Ecology and industrial input-output analysis has been offered (Duchin, 1992). This is again more useful for assessment of an existing system and less for design of a new one.

There are many papers that contribute to development of these tools for assessment of standard problems, or sophisticated versions that address network, firm or product specific problems. The next section assesses the applications and classifications of industrial ecology. The assessment tools outlined above have been used to assess examples in each of the classifications. A review of these detailed assessments for each classification is beyond the scope of this thesis.

2.4 Classification and assessment of Case Studies

Marian Chertow gets most credit for shaping industrial ecology into a clear scientific field, although earlier studies and breakthroughs precede her work (Cote & Cohen-Rosenthal, 1998). Chertow's 2000 article entitled Industrial Symbiosis: Literature Review and Taxonomy (Chertow M. R., 2000), followed her 1997-2000 project on eco-industrialism. The paper narrows the scope from the broad context of sustainable development and solidifies the

concept of industrial symbiosis. Chertow “focuses on predominantly commercial and industrial activities that include a materials exchange component to qualify the activity as industrial symbiosis.” Chertow continued to supply supporting evidence for industrial ecology through Yale Industrial Ecology class projects (Chertow, Portlock, & Coppock, 2002). The 2000 article provides empirical evidence of Industrial Ecology in practice, summarizes tools and approaches, and discusses the key issues related to sustainable development opportunities and challenges in industrial ecology. This article is the single most referenced in all subsequent Industrial Ecology papers (Yu, Davis, & Dijkema, 2013). It is fitting for this thesis to use Chertow’s study that legitimized Industrial Ecology as the basis for literature research. The article succinctly and logically organizes previous work, and categorizes the (then present) state-of-the art of the in terminology, categorization and examples." It synthesizes the limited available history of industrial ecology, and focuses on twelve case examples.

As with most industrial ecology articles up before 2005, Chertow focuses on the concept of eco-industrial parks, but does qualify that industrial symbiosis does not necessarily take place within the boundaries of a “park”. Chertow uses the experience from these examples to categorize industrial symbiosis models by organizational structure and spatial scale.

Organizational Structures according to Chertow in 2000:

- (Within one) Facility or Firm
- Inter-Firm
- Regional/Global

Eco-Industrial Park Models Types according to Chertow in 2000:

- Type 1: through waste exchanges
- Type 2: within a facility, firm, or organization
- Type 3: among firms collocated in a defined eco-industrial park
- Type 4: among local firms that are not co-located
- Type 5: among firms organized “virtually” across a broader region.

These classifications are a useful starting point. This thesis extends Chertow's categorizations five alternative classifications that provide a perspective reflecting the modern state of industrial ecology (Table 4). Context and clarity is given using case literature reviewed, where the conclusions and discussions offer insights and lessons from each study. The five classifications combine both spatial scale and temporal existence in literature.

The practical cases add to the collective body of knowledge and experience that can drive advancement of future applications and planning. Yu and colleagues point out that the number of these studies has exploded since 2006 (Yu, Davis, & Dijkema, 2013). This thesis suggests that it is not useful to compile a comprehensive review of all case studies of industrial ecology and industrial symbiosis in practice. Instead, the most thoroughly studied, informative and representative examples of case studies available in the literature are discussed in the next section.

Table 4 - New Classifications of Industrial Ecology Types

Classification	Summary
An industrial symbiosis (IS)	Cooperative exchange of material, energy, water, or utilities between firms, which are not the primary product of either firm
Eco-industrial Parks (EIPs)	Localized symbioses based on a defined geographic proximity
Urban Symbiosis	Focused on cycling resources within and around populous areas such as cities
Eco-industrial Networks	Multiple industrial symbioses either without a defined geographic scale, or across broad regions
Circular Economy	Idealized state of fully integrated economic, social, and environmental ecosystems

2.4.1 Industrial Symbiosis (IS)

There are many definitions for ‘industrial symbiosis’. In the context of the Table 4 classifications, industrial symbiosis is used in its most elemental tense as a cooperative exchange of resources between industrial actors which are not the primary outputs of either firm. Since the introduction of industrial symbiosis and similar phrases, numerous case papers were published. Many more unpublished cases exist in industry with some examples of industrial symbiosis in operation years before the term appeared (Erkman, 1997). Papers focusing on formation of single industrial symbioses from strategic planning perspectives often assess the first seeds for growth of more integrated eco-industrial systems (Chertow M. R., 2007) (Lowe, 1997). Most often they study technological connections and chemical processes of industrial symbioses, or improvement to energy and resource use. Other subdivisions of IS research address individual processes, products, or materials, particularly in the fields of chemical, bio-chemical and process engineering. Major funding comes from private and government Research & Development and from academic and non-profit research groups (Gondkar, Sreeramagiri, & Zondervan, 2012). A literature review of these studies is beyond the scope of this review.

2.4.2 Eco-industrial parks (localized symbioses)

Eco-industrial parks are the original industrial symbiosis application, and an easily grasped change from traditional industrial parks (Cote & Hall, 1995). The heuristic for depicting eco-industrial parks is a community of routinely co-located commercial actors or firms located in bounded geographic areas, connected by energy or material by-product flows. An old but still widely referenced definition is seen below.

An eco-industrial park is, “a community of businesses that cooperate with each other and with the local community to efficiently share resources (information, materials, water, energy, infrastructure and natural habitat), leading to economic gains, gains in environmental quality, and equitable enhancement of human resources for the business and local community” (President's Council for Sustainable Development, 1997).

To encompass all varieties of eco-industrial park developments the PCSD definition must use multiple ambiguous words that can't be measured like “efficiently share”, and references economic and environmental “gains”, and “equitable enhancement”. The definition does give a sense of the intentions of an eco-industrial park. Haskins provided a categorization of the Eco-Industrial Park types, in lieu of a single wordy definition (Haskins, 2007).

Table 5 - Seven Types of Industrial Configurations Often Defined as EIP's

7 TYPES OF ECO-INDUSTRIAL PARK?
A single by-product exchange pattern or network of exchanges (e.g., Kalundborg)
Recycling business cluster (e.g., Styria, Austria)
Collection of environmental technology firms
Collection of firms making “green” products
An industrial park designated around a single environmental theme (e.g., a solar energy-driven park)
A park with environmentally friendly infrastructure or construction
A mixed-use development (i.e., industrial, commercial and residential)

Groups of firms in any of the seven types in Table 5 may or may not qualify as *eco-industrial parks*, or as different to any typical industrial park or agglomeration economy. However, the combination of the PCSD definition for *intention* of eco-industrial parks and Haskins classifications outlining *structure* can be a qualitative heuristic for distinguishing industrial from eco-industrial developments. Agglomeration economies are industrial clusters that locate operations close to one another to gain benefits of proximity, such as personal business relationships, access to suppliers and/or customers, and short supply chains. Many industrial clusters share some characteristics with industrial ecology like material exchanges, utility sharing, or other resource efficiencies (Chertow, Ashton, & Espinosa, 2008). In many cases the clusters exhibit an “anchor tenant”, characterized by large flows of materials and byproducts that are useable as feedstock for other firms or actors (Chertow M. R., 2000). It is argued that these features do not automatically define them an eco-industrial park (Koenig, 2005). They can show potential to evolve into eco-industrial parks, but need the intent of coordinated management or a collective effort in pursuit of industrial ecology goals.

Kalundborg

Prior to 2006, there was extreme emphasis on implementing industrial ecology through eco-industrial parks, which can be linked to the classic success story of the Kalundborg Industrial Symbiosis in Denmark. Kalundborg is well documented and the subject of dozens of research studies. The aims of early research tried to understand how the industrial symbiosis at Kalundborg grew (Lowe & Evans, 1995) (Ehrenfeld & Gertler, 1997), or quantify the economic and ecological success of Kalundborg (Lowe & Evans, 1995) (Jacobsen, 2006). Most articles reviewed for this paper paid some reference to Kalundborg and its influence on other attempted industrial communities. A contentious issue is whether such a system can be planned. The lessons of these and consequent studies were important in defining sustainable development and in shaping governmental and corporate policy.

1 Surface Water	1961	12 Yeast Slurry	1989	23 Waste	2004
2 Gas	1972	13 Sulfur Fertilizer	1990/2001	24 Sea Water	2007
3 Surface Water	1973	14 Tech. Water	1991	25 Steam	2009
4 Biomass/NovoGro	1976	15 Gas	1992	26 Condensate	2009
5 Fly Ash	1979	16 Gypsum	1993	27 Straw	2009
6 Heat	1980/89	17 Waste Water	1995	28 Bioethanol	2010
7 Heat	1981	18 Drain Water	1995	29 Lignin	2010
8 Steam	1982	19 Sludge	1998	30 C5/C6 sugars	2010
9 Steam	1982	20 Fly Ash	1999		
10 Surface Water	1987	21 Deionized Water	2002		
11 Cooling Water	1987	22 Water	2004		

Figure 7 – Kalundborg Symbiosis Exchanges Legend (Kalundborg Symbiosis)

The Kalundborg Symbiosis is a reference point for much of this thesis' discussion. The technical and chemical processes and linkages that are often identified for industrial symbioses are seen at Kalundborg (Figure 7). Kalundborg exemplifies the bilateral bonds between actors in industrial symbioses. It also shows steady growth in number and strength of relationships over several decades - a relatively long time in economic, governmental, and

societal terms, if not in natural environmental terms. It also influences the later sections on the social aspects and enablers in planning and management of industrial symbiosis.

Figure 8 – Initial Kalundborg Symbiosis Exchange Development 1961-1979 (Kalundborg Symbiosis)

Kalundborg's industrial symbiosis growth traces back to 1961, when Statoil (then Esso) agreed with the local municipality to share the local water resource Lake Tisso, and the first pipes were laid (Kalundborg Symbiosis). More connections grew as firms saw the economic opportunities of using by-products created by Kalundborg's industry. The foundational linkages were added in 1972 and 1973. A local gypsum producer named Gyproc was added to acquire excess gas from Statoil for oven drying in plasterboard production, and Dong Energy (then the Aesnes Plant) was connected to the shared municipal water supply pipes, and subsequently to the cement industry for cooling water and returning steam. The volume of connections continued to increase. The latest exchanges were added in 2010.

Figure 9 – Kalundborg Symbiosis Exchanges 2000-2010 (Kalundborg Symbiosis)

Some important characteristics of Kalundborg’s development and growth:

- 1) It was not a planned system. It grew over four decades through bilateral business relationships focused on the economic, technical and logistical advantages (market forces), initially with environmental advantages considered as a subordinate added bonus.
- 2) Kalundborg did not identify itself as an “industrial symbiosis” until 1989, when the interconnections were discovered by a local high school project (Kalundborg Symbiosis). Only after academic, local government, NGOs and industry studies did a central municipal organization emerge at Kalundborg to manage and facilitate the expansion of symbiotic network.

Eco-industrial Park Planning Approaches – Central planning versus facilitation

The best approaches for developing eco-industrial parks, industrial symbiosis or industrial ecology in general is very heavily debated in the literature. Agreement still hasn’t

been reached. Also debated are the factors influencing success in industrial ecology. Some industries have slowly absorbed industrial ecology into their corporate strategy, and a consensus that it is *possible* to plan implement industrial ecology is growing (Ellen MacArthur Foundation, 2012) (Ellen MacArthur Foundation, 2013) (Stuchtey, 2013).

There are two competing planning approaches deliberated in the Eco-industrial Park literature; ‘centralized planning’ versus ‘self organizing’ systems. Chertow’s 2007 article explores planning approaches for industrial symbiosis. Fifteen PCSD-planned Eco-industrial Park projects are compared to twelve unplanned ones from around the globe (Chertow M. R., 2007). The researchers on this project had deep theoretical and case based experience in the field. They advocate policies and practices to stimulate market driven symbiotic connections. “Uncovering” of the “kernels” of symbiosis should take place, followed by facilitation of growth and evolution. Chertow and Ehrenfeld build and extend this theory in “Organizing Self-Organizing Systems” (Chertow & Ehrenfeld, 2012). In the paper they categorize eco-industrial developments into five planning categories: The Build and Recruit Model; the Planned Eco-Industrial Park Model; The Self-Organizing Symbiosis Model; The Retrofit Industrial Park Model; and the Circular Economy Eco-industrial Park Model. Many factors affect planning approach decisions. The dichotomy of planning approaches between central planning and market forces, is argued in the literature across all five of the classifications offered in this thesis, and has been fiercely and publicly debated (Lifset, 2008). These debates must be accounted for in the planning approach offered in this thesis.

Eco-industrial park case examples

Eco-industrial Park development reached different degrees of visibility in various national and international strategies, with various planning approaches and timelines. They

were a major focus in the 1990's into the 2000's for governments as an actionable sustainable development policy, in Developed and Developing countries. Nations incorporating eco-industrial park into strategy included the US and Canada, much of the EU, India, the Philippines, South Korea and China, among others (Koenig, 2005). The US became an early adopter of EIPs in their sustainable development strategy. Other significant early national attempts at Eco-Industrial Parks occurred in northwestern Europe (Heeres, Vermeulen, & de Walle, 2004).

The US Environmental Protection Agency funded a fieldbook for development of eco-industrial parks. A draft report was published in 1995 and a final report in 1996 (Lowe, Moran, & Holmes, 1996). The fieldbook came as US policy made eco-industrial park development a top priority through the PCSD's very public sustainable development agenda. The agenda was undermined by failed attempts to centrally plan and implement successful eco-industrial park projects (Gibbs & Deutz, 2005). Although the first national level attempts to implement industrial ecology failed, important lessons were learned and the need for further research was underlined (Gibbs & Deutz, 2007).

Aside from the examples already mentioned, many more published case studies similarly analyze and compare planning and operations of eco-industrial parks in several countries including but not limited to the US (Cote & Cohen-Rosenthal, 1998) (Gibbs & Deutz, 2005), Canada (Geng & Cote, 2002), Europe (Baas & Boons, 2004), Australia (Roberts, 2004), Brazil (Veiga & Magrini, 2009), South Korea (Oh, Kim, & Jeong, 2005) (Park & Won, 2007) (Park, Rene, Choi, & Chiu, 2008), India (Bain, Shenoy, Ashton, & Chertow, 2010), and China (Geng, Zhang, Cote, & Qi, 2008) (Shi, Tian, & Chen, 2012).

2.4.3 Urban symbiosis (Japanese Eco-Towns)

Urban Symbiosis can be understood as a subdivision of industrial ecology, and incorporates many of the same features as the industrial symbiosis ideology. The term extends industrial symbiosis to incorporate socio-economic metabolism, urban planning, waste management, recycling, sustainable cities, and related sociological, anthropological, public policy, architectural and engineering fields. The earliest and best-defined view of urban symbiosis is the 1997 Japanese Eco-Town Program. This was a national Japanese attempt to foster industrial symbiosis through systemic recycling. The program arose around the same time as eco-industrial parks and other industrial symbiosis programs, but can be viewed as a progression beyond classic *industrial* symbiosis due to the inclusion of society (the *consumer*²) in the industrial production cycle. The Eco-Town began with legislation on waste disposal and recycling, which led to mining dense urban centers for resources instead of depleting natural virgin sources. The program is well documented in a paper by Van Berkel et.al (Van Berkel, Fujita, Hashimoto, & Geng, 2009). The term Urban Symbiosis is summarized in the paper as “seeking to maximise the economic and environmental benefit from close geographic proximity of industrial and urban areas” by harnessing flows of physical by-product (waste) materials from cities to serve as “raw materials or energy sources in industrial operations”. The authors portray the program and the policies that enabled and enforced it, as the result of impending environmental and economic problems for Japan in the late 1990’s. These include extreme pollution and loss of natural capital such as water systems, and an economic slowdown of many Japanese industries in the face of international competition and unfavorable domestic economics. The program was widely regarded as an

² The “consumer” is a common but controversial definition for the public “end user” of goods and services in much of the abstract discussion on sustainability

economic, social and environmental success, although it was terminated in the mid 2000's. The authors speculate that several factors call the economic endurance of the program into question. Increasing financial pressures from international markets created competition for high-grade by-product resources (urban waste prior to recycling), which reduced the flow of waste to Japanese recycling facilities, thus decreasing production levels and financial viability. Also, the legitimate economic viability was threatened further when the government ended Eco-Town recycling subsidies. The subsidies accounted for USD 1.65 billion, an average of 36% of funding for projects in the study. The authors also venture that this subsidy was the catalyst for significant private sector funding amounting to twice the governmental funding.

Three years later, Satoshi Ohnishi et.al published an econometric analysis of recycling projects performance in Japanese Eco-Towns (Ohnishi, Fujita, Xudong, & Fujii, 2012). In contrast to recycling studies on collection and separation methods, they developed two multi-regression models based on survey and cross-sectional data to analyze operational performance. Specifically the amount of waste treated and the operating rates of the facilities. Three insights result from the study: firstly, close geographic proximity of recycling facilities to the users of recycled products had a positive effect on operating rates; Secondly the subsidies that were considered so effective in establishing Eco-Town recycling projects, had no effect on the operating rates of the facilities themselves, only on the financial buoyancy; and lastly that improved operating rates were achieved through increased collaboration, as opposed to competition.

2.4.4 Eco-Industrial Networks

Another development in the zeitgeist of industrial ecology is defined here as eco-industrial networks **Error! Reference source not found.** This classification is inclusive of all

ontemporary (post 2004) and emergent studies of industrial ecosystems that don't necessarily fit into the classifications. The word "network" gives eco-industrial networks a very broad classification. A clear direction can be seen developing throughout literature reviewed. Volumes and sources of data are increasing, as is the sophistication of tools and software to process, analyze and share data, and the appreciation of the interconnectedness of global economic and industrial systems. This enables a broader scope for industrial ecology, beyond the narrow boundaries of co-located or proximal industrial symbioses. The literature has diversified to includes social networks, supply (chain) and logistics networks, recycling networks, industrial networks, and many other applicable areas that evidence networks. Eco-industrial Network or Industrial Symbiosis Network definitions are inconsistent and only loosely referenced or defined, typically as a subset of other terms or fields within industrial ecology.

Table 6 - Eco-Industrial Network Definitions in the Literature

SELECTED DEFINITIONS OF ECO-INDUSTRIAL NETWORKS AND INDUSTRIAL SYMBIOSIS NETWORKS FROM THE LITERATURE
"...a network of companies in a region, working in collaboration with the town" (Gibbs & Deutz, 2005)
"IS networks aim to harvest improvement potentials present at the inter-organisational interfaces via collaborative interactions among anthropogenic activities, mostly located within physical proximity to each other. Webs of synergistic linkages emerging within IS networks can allow improvements in the efficiency and effectiveness by which different resources and capacities are utilised, going beyond that which can be achieved by fragmented pursuit of improvements in individual units." (Mirata, 2004)
"...effective symbiotic network of industries (i.e. energy efficient raw material acquisition, production, distribution and pollution treatment network)" (Oh, Kim, & Jeong, 2005)
"networks of EIPs at national or global levels" (Roberts, 2004)
"IS network (not necessarily park based) at a minimum should comprise three companies exchanging at least two different by-products" (Chertow M. R., 2007)

An inclusive definition is proposed below that can be used to describe an ideal state of eco-industrial networks, industrial symbiosis networks, and industrial ecosystems:

“Demand, process and intent driven systems of commercial actors interconnected with the markets for their products and services in a network that perpetually innovates to coordinate flows and/or sharing of materials, energy, information, utilities, or other resources to achieve profit for all stakeholders in the network and improvements in societal factors, where designed changes to the network or the products and services therein always have the net result of improved environmental impact.”

This proposed definition includes a deliberate balance of constraints and flexibility. Built into this definition is a set of minimum requirements, without a prescriptive framework for structure, planning or operation. There are aspects that are absolutely necessary and without which sustainable economic, social and environmental improvement is impossible. The system-based scientific view infers a high level of understanding of flows, interconnections, dynamic equilibrium and feedback loops. “Commercial actors” is used instead of ‘industrial’ actors so as to include greater diversity of eligible actors. The inclusion of markets for products and services within the network mandates the consideration of the industrial/commercial customer, and the public customer demand for products and services as a part of the network, not only an end-of-chain consideration. The inclusiveness of this definition can empower the market to influence decision-making. It should also influence production and location decisions to incorporate the supply to the markets for their products and services and the post-market supply of resources within the network. The term “perpetual innovation” sets a requirement for continuous reassessment and evolution. The aim is collaboration for continually improved market satisfaction and healthy competition. The societal factors of low unemployment, fair compensation, quality of work, quality of life, satisfaction of purpose etc., are defined as a goal for the network that is equal to economic

gain. Every member of the network should achieve economic gains greater than it would were it not a member, or greater competitive advantages.

The final clause recognizes the history of creative destruction throughout every economic and technological revolution (Graedel & Allenby, 2010), and requires that any changes to the structure, membership, culture or operation of the network is not made at the expense of environmental impact. Over time the environmental effects should improve, and must never regress. Several notable factors are omitted. Only two types of entities are included in the network: commercial actors, and the markets for their products or services. Government bodies are not explicitly included in the network, nor from it. In this definition, individual firms act in their own interest through market mechanisms, and are not restricted to one body's governance. The structure of planning and facilitation is left open to intelligent regulation, legislation, facilitation and other methods governing bodies can use to influence in ways that meet local, regional and global requirements. Another notable omission is the spatial dimension of the network. Within the constraints of this definition, companies are free to explore geographic linkages and opportunities that make economic, social and environmental sense for the member firms and the related product and service markets. This aspect of serendipity versus strict central planning is referenced later in this chapter. The spatial dimension of industrial ecosystems discussed in the next section in greater depth.

Spatial Analysis of Industrial Ecosystems

The understanding of boundaries and classifications in industrial ecology increases with the number of published cases studies. (Yu, Davis, & Dijkema, 2013). There has emerged an apparent consensus that spatial scale is an appropriate reference tool for *describing* industrial ecosystems, but it has also been successfully argued that spatial scale *alone* is not necessarily

useful for *design*, indicative of type or classification, or of eventual *success*. The Chertow and Lombardi definitions referenced earlier in this chapter both have extensions that incorporate geographic scale. At the time of Chertow's reference in 2000 the limited evidence from the undiversified field of industrial symbiosis implied that geography was a major planning, assessment and success factor. She writes,

"The keys to industrial symbiosis are collaboration and the synergistic possibilities offered by geographic proximity."

By 2012, Lombardi and Laybourn were both experienced practitioners in applications of industrial symbiosis in the United Kingdom. They state that,

"Although geographic proximity is often associated with IS, it is neither necessary nor sufficient—nor is a singular focus on physical resource exchange."

Although geographic proximity is explicitly excluded from Lombardi's definition, a simpler and competing British definition by the National Industrial Symbiosis Programme (NISP) states that IS simply as *"the establishment of close working agreements between normally unrelated companies that lead to resource efficiency. Working agreements include, among others, the direct reuse of one company's waste stream as another's raw material, the innovative reprocessing of problematic by-products and the sharing of underutilised power, water and/or steam."* (Jensen, Basson, Hellawell, Bailey, & Leach, 2011) An absence of any relation to geography in the definition is noted. However, the same journal article later states that geographic proximity plays a "key" role in industrial symbiosis, which they classify as a *"resource reuse and recycling practice"*. Jensen and colleagues go on to quantitatively support this assertion in a study of the geographical distances of IS in the UK. The study was confined to NISP cases in the UK, but the authors project it to be indicative of any developed country with diversified industry. They find the geographic distance of linkages between firms are

affected by product type (economic, environmental and regulatory feasibility of the linkage), social connections between decision makers (where proximity has a positive effect on social connection), and regulatory conditions. Distance is a necessary consideration in economic, environmental and regulatory calculations. This is supported in supply chain/circle theories.

The geographical component also causes significant challenges for assessment in design of new and existing networks. For example LCA and MFA analyses require well defined boundaries for calculation. Korhonen explores whether these tools should be used with a product-based focus, or a geographic focus (Korhonen, 2002). A product-based approach can span regulatory and geographic regions, but calculations are restricted to processes involved in production, use and disposal/recovery of a product, so can be calculated more easily than geographic approaches, which attempts to calculate all material and energy impacts for processes within a geographic area. Even if calculation was simple for both, the implications for planning and management using each approach also causes economic, political and environmental challenges. Simplicity may make calculation and change easier, but as discussed later in regards to resiliency, a broad scale can provide the most robust networks.

Theories of geographically expansive networks exist in earlier papers on “virtual” eco-industrial parks (Chertow M. R., 2000) and regional resource exchanges (Lowe, 1997). A case for increasing the scope of industrial ecosystem planning beyond park boundaries was made in 2004 (Sterr & Ott, 2004). Sterr and Ott analyze the eco-industrial park model and insist on consideration of the larger economic system. They stress that stability is impossible in the tightly “closed-loops” of eco-industrial parks. The Rhine-Neckar region in Germany is shown to have potential for a regional eco-industrial system. Although geographic boundaries are proposed for facilitation of the system, the authors suggest an evolutionary growth pattern and “open system” that would aim for a “large variety of roundput systems”. Thus boundary

constraints are porous instead of closed. Sterr and Ott believe that large spatial scale allows for greater input-output matches for firms in the region and success of industrial symbioses. But they acknowledge that increased distance makes personal contact in cooperations more difficult, impairing community alignment. In addition to the challenges of growth and geography, Sterr and Ott explore the technical, economic, and regulatory feasibility of such an eco-industrial network. They touch on design and decision-making challenges outlined in by Lowe and Evans in 1995 (Lowe & Evans, 1995).

The most important types of leadership in practical implementation of industrial ecosystems is the National Industrial Symbiosis Programme (NISP), a Business Council for Sustainable Development (BCSD-UK) product. NISP was launched in 2000 to “*coordinate the efforts to systematically catalyse the development of an IS network*” (Mirata, 2004). The NISP is Britain’s primary pursuit of industrial ecology, but encompasses only one portion of the UK’s efforts towards sustainability (Department of Environmental, Food & Rural Affairs). NISP still receives government funding, but is privately operated. Its operation can be considered industrial ecology consulting. The NISP Network self-identifies its role as,

“‘Connecting Industry and Creating Opportunity’ for business...helping companies cut disposal, storage and transport costs and generating sales by adding value to previously under-used or discarded resources...” and identifying “mutually profitable links or synergies between its business members so that underutilised and under valued resources from one (materials, energy and water) are recovered and reused elsewhere in the industrial network - creating a truly CIRCULAR ECONOMY!” (NISP, 2014).

NISP’s success in the UK enabled its leadership to expand globally in 2005 as International Synergies - Industrial Ecology Solutions. NISP is now a subsidiary program of the international group (International Synergies Limited, 2014). The International Synergies website states it is “*Striving to lead the world in Innovative Industrial Ecology Solutions for a low carbon, sustainable economy*” through a “*demand-led facilitative approach*”. Both

organizations employ similar frameworks to facilitate industrial ecology and create industrial symbiosis networks.

NISP and International Synergies identify existing firms or groups of firms with potential for industrial symbiosis. The organization built an extensive database of materials, energy, resources, and best practice techniques for industrial production processes and synergies. The knowledge is acquired through NISP's operations and through scientific research. Identifying potential linkages between firms and understanding the business relationships, missions, economic climate, and regulations, allows NISP and International Synergies to successfully establish industrial symbioses. Both organizations also provide support in building cooperative leadership within a network of companies, and continue to enable and advise network members on continuous improvement and expansion of the number of symbioses.

NISP leadership is a mixture of experienced operations professionals with successful backgrounds in various branches of sciences and engineering. This enables involvement from the finest scopes of technical feasibility to the highest leadership levels of firms. NISP operates at no cost to the network participants (Lombardi & Laybourn, 2012). As facilitators, NISP undertakes the task of brokerage and feasibility tests that time-constrained companies cannot afford in their daily operations (Costa & Ferrão, 2010). NISP has been in operation for over eight years with a multitude of successful case examples. They are the self proclaimed 'first ever National Industrial Symbiosis Program' (Paquin & Howard-Grenville, 2012). The keys to current and future success of industrial symbiosis are multi-level communication, collaboration, and funding, between industry, International Synergies, government policymakers, and regulators (Laybourn & Lombardi, 2012). Quantified success of the NISP are cost savings of GBP 1 billion, added sales revenue of GBP 993 million, and the creation of over 10,000 jobs in the U.K. (Ellen MacArthur Foundation, 2013). Two less quantifiable but

significant factors in NISP success are the methods for identification and indexing of suitable industrial symbioses (Jensen, Basson, Hellawell, & Leach, 2012), and the expansive database of possible synergies for all industries. The database includes technical coefficients, materials, techniques, costs, benefits, and best practices for implementation. The networks within NISP have various geographical distances, almost all are within the UK.

This UK example is not a planned attempt at building new eco-industrial actors. It is a collection of coordinating bodies that enable market driven programs designed to unveil the potential of fiscal and ecofriendly benefits by networking the well established industries of a developed economy (Boons, Spekkink, & Mouzakitidis, 2011) (Domenech & Davies, 2011).

The definition of eco-industrial networks offered at the beginning of this section is intended to extend the NISP model. The anticipation is that the definition will be implied by ‘global industry’ or ‘economy’ in future if conservation and recycling of materials, energy and resources becomes embedded in socio-economic culture. The last of the five classifications offer is a grander attempt to incorporate industrial ecology into a sustainable, business-focused, global economic culture.

2.4.5 Circular Economy

The first four classifications all allude to industrial operations or another technical term in their title. All of those terms are absent in mainstream business semantics. “Circular Economy” is a phrase used since the 1990’s. This review only found the term in business vocabulary after 2012. The simple title of Circular Economy is relevant to society. The word “Circular” has a vivid and easily understood meaning related to shape. The circle is an antonym of linear, and so implies a connotation to cycles. “Economy” is a commonplace expression found in news broadcasts concerning the financial and commercial systems that

drive global society. But “economy” can also be understood to imply efficiency, thrift, or savings. Thus the intended meaning of Circular Economy is clear and positively comprehended by the public and industry. Public and commercial opinion of industrial ecology is of paramount importance for global implementation of the circular economy.

The five classifications so far show the chronological progression of concepts, and increasing scope in industrial ecology. They also show a planning transition from detailed operations and tactics to corporate and governmental strategy. We can interpret the traction of industrial ecology in corporate and governmental strategy, by highlighting the recently published “Questions and Answers on the Circular Economy” (Stuchtey, 2013) through McKinsey & Company. McKinsey & Co. is a leading global strategic management consultancy. They have considerable experience in sustainability strategy at executive levels of private industry and governments. The article reinforces many of the points made in the industrial ecology literature, and unveils the corporate viewpoint. This viewpoint is fully realized in the multi-part “Towards the Circular Economy” report by the Ellen MacArthur Foundation in conjunction with McKinsey & Co. The report explores an economic analysis (Ellen MacArthur Foundation, 2012) and a consumer products perspective (Ellen MacArthur Foundation, 2013). In these reports, Circular Economy mainly envisions and quantifies economic opportunities, but also details the social and environmental opportunities of the Circular Economy in relation to the industrial and socio-economic systems of developed countries. The context of Circular Economy in this report extends far beyond the Chinese interpretation outlined in the next section. The EMF report concludes that up to 50% of the USD 3.2 trillion of material value in global supply chains alone could be recovered through implementation of circular economy principles, with USD 380 billion of potential net material cost-savings in the EU alone. The report asserts that the UK could apply circular economy to

the food and beverage industry and generate USD 1.5 billion in revenue, in addition to environmental, agricultural and fuel based benefits. The study frames a convincing quantitative argument for immediate action. It also details several tremendous challenges ahead, but claims that much of the work in design, heuristics and feasibility studies has been done, and now is time for the ideas to be spread to economies, industries and countries at scale.

Circular Economy in China

China has moved quickly to establish its own unique and ambitious, government led approach to sustainability and industrial ecosystems. China's policy is also titled Circular Economy. The overarching principles of the Chinese Circular Economy are the same as the EMF report, but the Chinese 'top-down' application via centrally planned policy does not reflect the prescriptive methods or full range of benefits suggested by the EMF report. China's development of Circular Economy has been monitored from a distance by developed countries as they foster their own strategies, and the EMF report provides a bridge to implementation.

Distinctive cultural, political, economic and environmental structures define and shape China's national strategies. The strength of the government structures in this centrally planned economy enables rapid execution of strategies without much need to persuade markets or the public at large. This is advantageous when swift and substantial change is necessary, but creates legislative, competitive and economic uncertainty for industry. Such uncertainty could be crippling if enacted in developed free market economies where investors tend to be risk averse. The Circular Economy strategy in China has been an evolutionary approach to mitigate the domestic and international sustainability pressures facing China. These pressures emerged during China's rapid industrialization. The country's massive economic growth over

the last three decades was primarily built on extremely high resource consumption (Fang, Cote, & Qin, 2007). Yuan et al. gave the first significant insight into China's Circular Economy as a development strategy in 2006. He summarizes the scale as a three level approach: 1. The Micro or individual firm level, through effective identification, use and sharing of by-products; 2. The Meso or EIP level, pursuing industrial ecology; 3. The Macro or regional "eco-city, eco-municipality or eco-province" level, creating and improving recycling systems (Yuan, Bi, & Moriguchi, 2006). This is a very similar framework to that proposed by Chertow for industrial symbiosis and eco-industrial parks (Chertow M. R., 2000). The popular "three level" perspective in industrial ecology is further broken down by Fang et.al into a five level structure for the Chinese Circular Economy (Figure 10) and later divided into seven levels by Sarkis in relation to Green Supply Chain Management (Sarkis, 2012). Fang et. al show five levels of increasing geographic scale on the Y-Axis, and increasing levels of Industrial Sustainability on the X-Axis. The authors don't clarify the meaning of Industrial Sustainability, but it is assumed to mean decreasing environmental depletion and increased resource efficiency. Five circles of increasing size with distance from the origin show the scale and complexity of each system. The far right side of the figure shows the State Environmental Protection Agency's (now known as the Ministry for Environmental Protection or MEP) ratified examples of circles.

Figure 10 –Scale of Eco-Industrial Development in China (Fang, Cote, & Qin, 2007)

The smallest and least sustainable of the five eco-industrial operations according to the five-level structure is the Eco-Industrial Park, considered the “Community Level” of Eco-Industrial Development, and at the time of publication there were thirteen ratified eco-industrial parks according to SEPA. The authors offer the Eco-Industrial Network at the “County Level”, considered in this context to be a network of eco-industrial parks. At the city level a much larger circle shows the Demonstration City for CE, and Guiyang City is provided as an example. The information provided on Guiyang City has many similarities to the Japanese Urban Symbiosis but reflects a more inclusive scope, with boundaries beyond recycling and production that integrate into the “circular economy”. The next level of the scale is the Province Level, which presents Liaoning Province in China’s northeast as an example of a Circular Economy region. The highest level of the scale is the National Level. There is no consideration of international markets, trade, or synergies in this scale. Circular Economy in China is portrayed in literature as a strategy to address pressures solely for China’s benefit, without consideration of the broader global picture. It is acknowledged internationally that the

scale of China's industry and domestic challenges are significant, and positive environmental effects of Circular Economy in China will be felt globally (Fang, Cote, & Qin, 2007).

The immediacy of China's environmental and resource problems required swift action. China acted to implement Circular Economy with speed and decisiveness at a scale unprecedented in sustainable development. The first ten years of China's Circular Economy evolution at a national strategy level is summarized in Figure 11. China's bold model is a valuable example for other national and international planning approaches to learn from, but not necessarily follow.

Figure 11 – China's CE Evolution (Author defined based on literature review)

After cautiously opening their economy to international markets, the Chinese central government (the State Council) rapidly invested in technological and economic development. It designated Economic and Technological Development Zones (ETDZ) around 14 coastal cities in 1984, where foreign investment and trade were enticed through extremely favorable financial and environmental regulatory conditions (Geng & Hengxin, 2009). The Chinese economy has since grown at a ferocious pace, with GDP growth over 9% annually (Tan, Zhu;

CESC, 2006). Manufacturing and heavy industry boomed along with burgeoning population growth. Consequently, serious problems of environmental degradation, pollution, and resource depletion manifested at similar rates. The need for immediate change was clear in China and to the international community. Cleaner Production concepts developed in Europe (Ashton, Luque, & Ehrenfeld, 2002) were enacted into national strategy and law in 1992 in the first major effort to decrease resource consumption and toxicity of industrial production waste from ETDZs (Zhu, Geng, & Lai, 2010). In 1999 China's State Environmental Protection Agency introduced the first legislation encouraging development of eco-industrial parks, mainly by retrofitting ETDZ's to create waste based loops between companies (Geng, Zhang, Cote, & Qi, 2008) (Yuan, Bi, & Moriguichi, 2006). Industry was encouraged to be innovative, and the national policy reflects attempts to standardize and replicate successful approaches through ISO 14001 environmental standardization and auditing, and enactment of the Energy Economization law (Mathews & Tan, 2011). More central government agencies were added to support and enforce Circular Economy strategies and the Circular Economy Promotion Law was finally passed in 2009. The declarations of "National Demonstration" eco-industrial parks, zones, and developments at each stage of the circular economy evolution were intended to provide inspiration and guidance for increasingly successful and strategically acceptable development. Acceleration of the evolution of the circular economy was publicly announced in 2002 at the 16th Congress of the Communist Party of China. The "Strategic Plan for 21st Century Pursuing Circular Economy" laid out three paths to achieving a circular economy (Yuan, Bi, & Moriguichi, 2006):

- Industrialization pushed forward by information technology
- Sustainable development created by promoting a circular economy (CE) with optimal utilization of resources and energy
- Maximization of integrated community profit

Yuan et.al also provide insight into practitioners who were working to realize the circular economy in the early 2000's. They summarize these professionals as mostly engineers with environmental, chemical, or mineral process concentrations. They note that these engineers were involved in the experimental innovation of creating symbiotic connections and encouraging cleaner production, but that their projects often failed due to technological or cost issues and a lack of economic experience. However the cumulative experience of both failure and success provided frameworks for future development of demonstration parks and zones.

To exemplify the Chinese circular economy approach two of the first and largest ETDZs, now regional EIPs, are explored; Tianjin Economic Development Area (TEDA) and Dalian Economic Development Zone (Geng, Zhang, Cote, & Qi, 2008). Both in northeast China and lie on the coast of the Yellow Sea .

Tianjin Economic Development Area (TEDA)

TEDA was carefully studied by Shi et.al in 2010 (Shi, Chertow, & Song, 2010). They define TEDA as a mixed-industry park with subsidiaries of more than 60 non-Chinese Fortune 500 companies, undergoing a facilitated transformation into an eco-industrial park in the context of China's Circular Economic reform, predominantly through cleaner production and pollution prevention. The authors offer three important factors of successful facilitation at TEDA:

- The culture of innovation, experimentation and continuous evolutionary change is ingrained in TEDA leadership and member culture. This fosters cooperative learning, spread of best practices, and ability to consistently absorb the ongoing expansion and failure of firms and symbiotic exchanges.
- TEDA's governing body (TEDA Administrative Commission) coordinates firms and sets

local legislation. The pro-business sensitivity and economic intelligence of both is cited as a major factor in securing economic success for member firms, and the symbiotic exchanges between them, which aids the whole network.

- The TEDA leadership's outward perspective combined with an introspective focus consistently creates incentives and public policies to out-compete for foreign investment to maintain its position as a leading eco-industrial park.

Dalian

The Dalian Economic Development Zone is a prominent example of pioneering city-based progress towards the circular economy. Geng et.al provide a quantitative study of the practices and results of strategies in Dalian, citing a predominant focus on capturing the benefits of preventing waste at the source as well as turning waste into a resource, a CE can reduce both waste to be treated and levels of resource consumption (Geng, Zhu, Doberstein, & Fujita, 2009). The authors celebrate the municipality's promotion of Circular Economy principles through financial incentives, and development of member involvement in circular economic initiatives. Despite championing the example of Dalian, the authors caution use of Dalian as a universal heuristic framework, encouraging planners to consider both local and global factors.

Despite the China's two decades in pursuit of an environmentally sustainable, and economically successful industrial ecosystem, Yu et al. report only one article relating to China in the top 15 most cited papers in the industrial ecology literature from 1997 to 2012.

The classifications offered in this thesis are not definitive. They provide a point of reference to portray the chronology of development in industrial ecology concepts, with some reference to the *typical*³ geographic and organizational scale of the cases, and an indication of the pace of change and integration. There are examples within the literature reviewed that could span multiple classifications, and some that may not fit into any of them.

The original modeling problem addressed in this thesis is forced to draw narrow boundaries around the system and accept an overly focused scope of only a small number of symbiotic relationships. This is only to illustrate the basic principles necessary for modeling industrial symbioses. The second problem in this thesis reflects the logical necessity to reopen the scope and boundary to add or remove actors from an industrial symbiosis, in order to achieve maximal success, and to adapt effectively over time. Both of these models fit into the fourth classification of “eco-industrial networks”.

2.5 Qualitative Assessment of Planning Approaches and Examination of Growth/Evolution in Industrial Ecosystems

In the nascent field of industrial ecology during the 1990’s there were few case examples of industrial symbiosis and most of the cases identified focused on heavy industry and other process based industries. Intuitively it follows that IE start with the high volume, most environmentally impactful areas. The literature reveals that the efforts to discover and facilitate industrial ecology in practice increased sample sizes and diversified the scope. A knowledge base emerged of the technical materials, energy, and resources that can be exchanged, the potential advantages that motivate and reinforce the necessity of industrial

³ “Typical” as adjudged by this thesis’ authors, based on the number of references to a particular spatial scale, or our assessment of the theoretical weight of the articles that reference or allude to geographic scale

ecology, and the conditions or approaches for these exchanges to be implemented. Chertow and Ehrenfeld's 2012 article on the realities of "organizing self-organizing systems" backs a balanced approach of market-based initiation, and facilitated assistance to grow embryonic industrial symbioses. The authors support both 'hard' quantitative and 'soft' qualitative techniques and tools (Chertow & Ehrenfeld, 2012).

The technical compatibility of firms, products, industries and processes gained through Input-output matching, is an important factor for eco-industrial planning (Chertow M. R., 2000). Attempts to plan eco-industrial developments using input-output matching alone have typically proven insufficient (Heeres, Vermeulen, & de Walle, 2004) (Baas & Boons, 2004). The databases of information gained from the failed examples of input-output matching, like those developed by Bechtel Corporation in the Brownsville, Texas case, the "Matchmaker!" program at Yale (Chertow, Portlock, & Coppock, 2002), and the NISP catalogues have been invaluable (NISP, 2014). Other lessons were learned from failures. Despite frequent failures, it is clear in the literature that the motivation to plan, coordinate or facilitate industrial ecology from a network perspective prevails as the best accelerator of sustainable principles.

An insight into the 'softer' human sciences of IE developments, such as government policy, was published by Lowe in relation to EIPs (Lowe, 1997), then again at larger scope by Sterr and Ott (Sterr & Ott, 2004), who also pointed to the interpersonal relationships between competing and cooperating firms in a connected geographical region.

Reid Lifset, a Yale resident scholar and Editor in Chief of the Journal of Industrial Ecology, wrote in an introductory editorial a synopsis of the industrial ecology zeitgeist (Lifset, 2008). He highlighted the academic transition from scientific (natural sciences and engineering) analysis to a more inclusive approach to industrial ecology. He advocated a

“balancing and melding” of quantitative assessment and qualitative consideration in the field, accounting for more than just policy research. By “Qualitative” he references social sciences like “economic sociology”.

This thesis tends to agree with Chertow, Ehrenfeld, Lifset and the other authors referenced above on the balanced, holistic, inclusive approach to planning eco-industrial developments. Planning teams require technical and scientific knowledge and skills, and expertise in economic and market principles, government policy. The approach facilitates social networking, collaboration, and appointment of effective network management. These combinations are required to achieve successful eco-industrial networks as a part of circular economic principles. An understanding and calculation of risk, resiliency, diversity and lifecycles are fundamental to effective implementation.

In the next section of the review the planning methodologies are synthesized from articles pertaining to the five classifications offered above. and the proliferation of techno-social studies in industrial ecology are discussed.

Lifset’s editorial provides a reference for the discussion of policy and its role in encouraging industrial ecology realization throughout national and global economies, toward the Circular Economy. He recounts a very public debate spanning multiple articles in peer-reviewed journals between two academics, Pierre Desrochers and Frank Boons. The disagreement is a high level discussion on government’s role in development of industrial ecology, and whether development should be driven by the policy (Boons F. , 2008) (Boons F. , 2012) or free-market means (Desrochers, 2000) (Desrochers, 2004) (Desrochers, 2012). Both authors provide deep historical evidence to support their case. Like Lifset, this thesis sees the

discussion as a maturation of industrial ecology beyond technical and natural science and into public policy, economic sociology, and behavioral sciences.

Boons very recently co-authored another policy-based industrial symbiosis paper. This time proposing a research agenda to evaluate the influence of policy. His key conclusion is the need for a dynamic legislative approach that can evolve with industry (Jiao & Boons, 2014). The authors also find no decisive evidence for the impact of legislation on industrial symbiosis. The models developed in this thesis show that legislation can have a significant impact on eco-industrial network feasibility, and dynamic legislation directly affects the second scenario explored by the model.

In a study of success factors like those proposed by Jiao and Boons, Yu et.al supported their conclusions. They conducted a case study of the TEDA eco-industrial park in China (Yu, de Jong, & Dijkema, 2014). The authors describe five key activities indicating successful facilitation of eco-industrial development. These are Institutional Activity, Technical Feasibility, Economic and Financial Enablers, Information Activity, and Company Activity. Each indicator exhibits policies, incentives, infrastructures, training and operations in a balanced scorecard approach.

A UK based study provides an alternative scorecard, a “Habitat Suitability Index”, in which the overriding principle is “fitting in” to the local environment, as opposed to conditioning the environment for industrial benefit. They advocate casual analysis of the local regulatory and social frameworks (Jensen, Basson, Hellawell, & Leach, 2012)

Another study provides a different perspective, addressing the leadership hierarchy of regional industrial systems through a social science analytical framework. The goal is to achieve a “prescriptive approach” that can stimulate industrial ecology (Baas & Boons, 2004).

The Authors study the INES Mainport 1999-2002 project in the Rotterdam harbor area, dividing what they term a techno-social approach into three phases; Regional Efficiency, Regional Learning, and Sustainable Industrial Districts. These phases show operational and strategic formations and deepening of bonds between firms at each stage. Domenech and Davies consider similar stages of Emergence, Probation and Development and Expansion (Domenech & Davies, 2011). The aforementioned “organizing self-organizing systems” offers Sprouting, Uncovering, and Embeddedness and Institutionalization in their three stage approach (Chertow & Ehrenfeld, 2012).

In an empirical examination of actions by the National Industrial Symbiosis Programme (NISP) in the UK over an eight-year period, Paquin and Howard-Grenville build on the concept of embeddedness. Embeddedness is described in the article as the “*impacts of actors’ social interaction patterns and practices on their economic and organizational actions*” (Paquin & Howard-Grenville, 2012). The study aims to gain insight into the effectiveness of planning and expansion patterns in industrial symbiosis networks, under different conditions and approaches. In their discussion the authors explore the qualitative social science approaches to analysis. They emphasize network orchestration theory (Dhanasai & Parkhe, 2006), which differentiates network processes into “serendipitous” and “goal-directed” processes (Kilduff, Tsai, & Hanke, 2006). Serendipity is the “happenstance of people meeting and liking one another,” and a goal-directed process is the case where “parties interact to achieve, plan, coordinate, or decide on their individual and collective activities” (Salancik, 1995). The 2012 study follows 2009 research by the authors exploring levels of embeddedness of NISP and firms they interact with, and the business relationships within industrial symbiosis networks. There was evidence in the original study to prove that the NISP practices are effective in facilitating industrial symbiosis networks. The 2012 article could not establish

consistent, significant quantitative cause-and-effect relationships of formation and growth factors for industrial symbioses, nor for patterns of successful facilitation methods.

The findings indicate the existence of unconsidered variables, suggesting that the relationship between actors and institutions are more complicated than suggested in the bulk of the literature. A Dutch study supports this conclusion (Boons & Spekkink, 2012). The authors close with a note that embeddedness is found “more between coordinator and firms than between firms”, and that the findings are consistent with goal-directed network processes of network orchestration theory. They also state that serendipity plays a larger role in formation, but over time relationships between actors become more goal oriented in networks. The theory supports this thesis. Network orchestration by a coordinating body is required in the planning of eco-industrial networks and the underlying structures therein (Scenario 1), but there is also a role for other factors to influence the network, and the role of facilitator or coordinator must continually assist the evolution of the network (Scenario 2).

Embeddedness theory relates to social contacts in networks. Many researchers use “Social Network Analysis” to quantitatively assess social aspects in industrial ecology (Domenech & Davies, 2009) (Boons & Spekkink, 2012) (Ashton W. , 2008). Ashton’s work provides a look at social network analysis, and studies the social aspects of growth, evolution and functionality of IS networks. The work has made efforts to measure the social concepts of “short mental distance”, “trust”, “openness”, and “communication” (Ashton & Bain, 2012).

Another aspect of eco-industrial network assessment was studied by Zhu and Ruth. They reconcile some of the same infrequently related fields as this thesis proposes. Their study relates to formation and growth of networks and their enduring survival as the network and

members experience disruptions (Zhu & Ruth, 2013). Their work explores resiliency of networks, which will be discussed again later in this thesis.

Junming Zhu and Matthias Ruth published an analysis of the growth of fifteen successfully implemented Industrial Symbiosis networks, including over two hundred firms (Zhu & Ruth, 2014). The objective was to predict the growth of collaborative exchanges at the system level. The institutional and formative conditions and related resilience was considered. The methodology follows research in complex adaptive systems theory in ecology (Walker, Holling, Carpenter, & Kinzig, 2004; Ottino, 2004) and supply chains (Christopher & Peck, 2004). The authors separate IS networks into three forming processes, “Preferential Growth”, “Homogenous Growth”, and “Random Pairing“. A scenario for each growth process is tested. The study concludes that industrial symbiosis formation follows a predictable pattern. The authors show that experience in industrial symbiosis improves a firm’s ability to form future linkages and likelihood to do so. The ‘learning by doing’ means experienced firms are more likely to absorb newly available linkages than are inexperienced firms. The authors believe this ‘preferential’ growth creates bias towards the oldest and most connected firms in terms of resiliency. Still, they suggest that “firm-organized or externally introduced coordination and strong government engagement” can change this preference and brokerage power of the most connected firms to improve capabilities of inexperienced firms, to create more homogenous growth with more equal ability to create linkages in a network. The concept of preferential growth is related in particular to “anchor tenants” as mentioned earlier in relation to clusters.

2.6 Indications and Lessons for Planning

“Industrial ecology is designed-in not added-on.” (Jelinski, Graedel, Laudise, McCall, & Patel, 1992).

Philips CEO Frans van Houten reinforces the emphasis on design in the transition towards industrial ecology, (“circular economy” in our context) through a discussion on Philip’s redesign of business models and product and service design evolution, in a published interview with McKinsey & Co (van Houten, 2014).

The literature in industrial ecology provides optimism but details many multi-faceted challenges and complexities. This review shows that it is vital at the earliest stages of planning that the multi-disciplinary goals and methods are identified, and the correct measurement for qualification or quantification are used. Techno-economic considerations are paramount to successful eco-industrial network planning and evolution. Connections and exchanges between firms must be technically feasible and be economically stable in the long term. Strategic goals of network actors must be in keeping with industrial ecology. Local and national policy must provide insightful and market based incentives for industry to pursue of industrial ecology as rational economic strategy, not merely a corporate social responsibility. Other major objectives should be socially astute, consistent facilitation to accelerate formation, scaling and maturation of resilient networks. Lombardi et.al are correct that planning and building an eco-industrial network ought to include facilitation of goal-oriented linkages and serendipitous connections (Lombardi, Lyons, Shi, & Agarwal, 2012).

Extension to IE Scope Required – Searching Other Topics

The next chapter reviews separate areas of research and industry. The overlap of methods is manifest of the interconnected and interdisciplinary nature of industrial ecology. The importance of communication and collaboration between researchers and practitioners in the Life-Cycle Analysis, Life-Cycle Management, and Industrial Ecology is noted in John Ehrenfeld’s 2003 editorial in the International Journal of Life-Cycle Analysis (Ehrenfeld J. R.,

2003). His discussion also incorporates several points made in this literature review, emphasizing priority of qualitative and quantitative design techniques for a sustainable future, over victory in assigning the vernacular to these areas.

This thesis contributes to the industrial symbiosis conversation with the addition of some terminologies and reference to theories from the distinct but related areas where considerable overlap occurs. The progress of research in green and sustainable supply chains, recycling, and waste management are important elements required in the discussion and modeling of industrial symbiosis. Much of the research reviewed above bears reference to these fields. The aim is integration of concepts and perspectives as they apply to industrial ecology.

CHAPTER 3 – REVIEW OF RELATED PERTINENT LITERATURE

There is a growing number of researchers and practitioners who have studied the fields of industrial ecology, industrial symbiosis, eco-industrial parks and circular economy. There is an established base of supply-chain researchers and practitioners in fields like reverse logistics and green supply chain management. There are additional experts studying and implementing product recycling and waste management systems.

The goal of this review is to portray a collective direction in these fields. It will be demonstrated that global planning and development in the field of industrial ecology can benefit from the unification of several professional disciplines and research fields. Through a multi-disciplinary understanding, quantitative modeling tools can aid effective planning of sustainable eco-industrial networks.

3.1 Supply Chain and Industrial Ecology

A Google Scholar search for articles containing “supply chain” returned approximately 781,000 articles. 83,600 of which included Supply Chain in the title of the article. From some of these papers a definition of supply chain was gained, as was an understanding of its pertinence to this thesis. A further search for Supply Chain literature that includes “industrial ecology” or “industrial symbiosis” numbered at approximately 12,000. Only 5 articles were returned a search for literature that includes supply chain and either industrial ecology or industrial symbiosis in the title.

However, a search for supply chain articles that mention “environmental” in the article returns about 358,000 articles, but only 518 with “environmental” and “supply chain” in the title. This suggests that environmental concerns are explored in many supply chain areas but

not under the title of Environmental Supply Chain Management. A similar search within supply chain articles for “sustainability” or “sustainable” returned roughly 214,000 results, of which over a thousand had one of these words in the title. These papers were broken down into the popular terms titles found within the top cited articles relating to sustainability and supply chain management. The highest returns were Sustainable Supply Chain Management, Green Supply Chain Management, Closed Loop Supply Chain, Reverse Logistics and Integrated Chain Management. These terms are frequently interchanged in the works and this thesis.

Table 7 - Bibliometric Review of Supply Chains in Relation to Industrial Ecology

Google Scholar Search Terms	Term Found in Article	
	Anywhere	Title
Supply Chain	781,000	83,600
Supply Chain AND “industrial ecology” OR “industrial symbiosis”	12,000	5
Supply Chain AND “environmental”	358,000	518
Supply Chain AND “sustainability” OR “sustainable”	214,000	1,090
Supply Chain AND “sustainable”	204,000	723
Supply Chain AND “sustainability”	144,000	382
Supply Chain AND “green”	95,600	1,450
Supply Chain AND “closed loop”	46,900	754
Supply Chain AND “reverse logistics”	36,100	149
Integrated Chain Management	561	22

A commonly cited definitions of the “supply chain” is:

“The supply chain encompasses all activities associated with the flow and transformation of goods from raw materials stage (extraction), through to the end user, as well as the associated information flows. Material and information flow both up and down the supply chain. Supply chain management (SCM) is the integration of these activities through improved supply chain relationships to achieve a sustainable competitive advantage” (Handfield & Nichols, 1999)

It can be added that supply chains are a macro, firm based and/or products based perspective of material, energy and information flows. Mentzer et.al offer a model of supply

chain management (Figure 12). They state that the goals and values of supply chains are customer satisfaction, value, profitability, and competitive advantage (Mentzer, et al., 2001).

Figure 12-Traditional Value Chain Components of Supply Chain Management (Mentzer, et al., 2001)

The evolution of supply chain management towards sustainability is captured in this definition of “sustainable supply chain management”:

“The management of material, information and capital flows as well as cooperation among companies along the supply chain while taking goals from all three dimensions of sustainable development, i.e., economic, environmental and social, into account which are derived from customer and stakeholder requirements.” (Seuring & Müller, 2008)

This definition can also be used for the related “environmental supply chain management”, “green supply chain management” and “integrated chain management”. As in industrial ecology, multiple competing definitions exist for each of these terms. However, there is more consensus on definitions in supply chain literature than in industrial ecology.

Linton, Klassen and Jayaraman present an overview of the interactions of sustainability and supply chains (Linton, Klassen, & Jayaraman, 2007). They review trends in supply chain

and optimization of supply chains, and track the broadening scope from individual firms to the entire supply chain for products and services; from raw material processing through customer delivery. The authors also show increasing research focus toward the end-of-life (EOL) recovery process for products. Six interactions between supply chain and sustainability are described: product design, manufacturing by-products, by-products produced during product use, product life extension, product EOL, and EOL recovery processes. A major theme in this article is apprehension in operations research towards reverse flows, remanufacturing, and recycling, and their added complexity, uncertainties and costs to supply chains.

Stefan Seuring appears prominently in supply chain research. In a 2004 paper, he investigated parallels between industrial ecology, life cycles and supply chains, uniting some of the ideas in this thesis. He argues that although differences exist between certain fields, there is theoretical cohesion that can advance development and implementation of sustainable development in each (Seuring, 2004). The overriding aim is collaboration between researchers across fields, although Seuring recognizes other aspects like economics related to the terms.

Based on the volume and content of supply chain literature, supply chain management and related fields appear more mature and better defined than industrial ecology. This makes sense since all firms making products must bring them to market via a supply chain. Thus understanding of supply chain is essential and deep expertise can create competitive advantages for firms, which leads to research. The same is not true with IE, although there is evidence in corporate missions statements that sustainability and industrial ecology is seen as a competitive advantage for firms, from design to resource recovery (Ernst & Young, 2013).

Chertow explicitly excludes supply chains from industrial symbiosis consideration (Chertow M. R., 2000), but does claim that corporations could assist the spread of industrial

symbiosis. This thesis insists that supply chains are central to industrial ecology.

Implementation of industrial symbiosis occurs within areas of supply chain operations.

Sustainability and IS have grown within multiple supply chain research areas. The lines between field definitions in supply chain literature are often vague, but clearer than in IE. Joseph Sarkis is a prominent supply chain researcher who has also spanned some of the gaps between IE, supply chains and sustainability. He condenses the concept of Green Supply Chain Management into five areas of engagement (Figure 13). These sub-categories are IE & IS, 'Environmental Management Systems', 'Product Stewardship & Extended Producer Responsibility', 'Life Cycle Analysis', and 'Ecodesign & Design for the Environment'. He succinctly captures some of the connections made in this thesis.

**Figure 13 - Industrial Environmental Practices in Green Supply Chain Management.
Based on (Sarkis, 2012)**

This thesis supports the fundamentals set out by McDonough and Braungart in the Hannover Principles. These principles declare design as the first piece of successful planning and application of sustainable development (McDonough & Braungart, 1992). They state that material choice and reduction of material volume has the greatest effect on economic and environmental costs. This also has the greatest effect on the logistics of supply chains (Rogers & Tibben-Lembke, 2001). A detailed review of the literature on design of products and services is beyond the scope of this literature review, as is a review of environmental management systems. Extended producer responsibility is briefly referenced in the recycling and waste management section.

Chapter 2 stated that professionals involved in the narrowest classifications of industrial ecology often have backgrounds in natural and/or technical sciences such as chemical engineers. The range of concentrations and skills expands as scope expands. A similar variation exists in supply chains. High-level supply chain roles are filled with business strategy professionals (Seuring, 2004). However, it is with narrowed scope of study in different areas of supply chain that the variety of backgrounds in research and operations increases. Backgrounds and expertise are similar to those in industrial Ecology. Duflou et.al provide some perspective for the scope of supply chains in relation to industrial symbiosis and sustainability (Duflou, et al., 2012). They discuss five levels of scope in their processes and systems examination of energy and resource efficiency in manufacturing. This begins at the narrowest scope, the micro level of a unit process, through multi-machine, factory, and multi-facility (industrial symbiosis) levels, up to the macro level of a supply chain. Sarkis also provides a framework for understanding the boundaries and flows of green supply chain management. The framework includes seven layers of operational function, five layers of scale, and nine forms of interrelated boundaries for consideration therein.

Figure 14 - Layers and Levels of Supply Chain. Based on (Sarkis, 2012)

This thesis addresses supply chain at a high level, omitting a detailed review of manufacturing and production processes, or logistics management. The discussion aims to connect established technical feasibilities at the basis of eco-industrial networks literature, and the economic and operational realities of supply chain planning. The similarities between the fields as they approach sustainability are apparent.

Supply chains are an important platform for the business case for operations of sustainability (Hawken, Lovins, & Lovins, 2010) (Lovins & Cohen, 2011). The global scale of multinational corporations offers the capacity to create positive impacts through transformation of supply chain practices and organizational culture. The example of Wal-Mart in Force of Nature shows of how impactful such changes can be, where even a 5% reduction in packaging for one product saves millions of dollars and millions of tons of carbon. Supply chains connect to every aspect of production and consumption of goods and services (Humes,

2011). It is infeasible to generate cultural and economic transformation without the engagement of supply chains and those who lead, design and operate them (Hudson, 2005).

The volume of research taking place under the title of Green Supply Chain Management was found to have increased dramatically, alongside but independent of industrial ecology (Srivastava, 2007). Srivastava provides insightful overviews of three main research areas in Green Supply Chain Management Design, shown in Figure 16. The author emphasizes the “green” side of supply chain management and design, but fails to capture the stakeholder/customer essence of the Seuring/Müller definition, or the Mentzer et.al defining model in Figure 12. The slogan “Reduce, Reuse, Recycle, Remanufacture” is considered regarding the reverse material and product flows through the Green Supply Chain (Kerr & Ryan, 2001). The slogan is extended to include Refurbish/Repair and Recovery. All of these “Re-“ terms also appear in Waste Management literature of the next section’s review of Recycling and Waste Management.

Pressures and incentives for sustainability in supply chains

Pressures and incentives	Number of papers (<i>N</i> = 191)
Legal demands/regulation	99
Customer demands	96
Response to stakeholders	90
Competitive advantage	71
Environmental and social pressure groups	38
Reputation loss	30

Figure 15 – Sustainable Supply Chain “Triggers” (Seuring & Müller, 2008)

In a 2008 literature review of sustainable supply chain management, Seuring and Müller offer six “triggers” that motivate firms to shift toward sustainable supply chain management Figure 15. The scope of that review combines supply chain management and sustainability management. They propose two more sections of supply chain research, ‘supplier

management for risks and performance’ and ‘supply chain management for sustainable products’.

Figure 16 - Classifications within Green Supply Chain Design (Srivastava, 2007)

Seuring and Müller’s 2008 review summarizes research conclusions as making three main points (Seuring & Müller, 2008). Firstly, supply chain research must urgently expand to examine ‘end-to-end’ supply chains for a complete sustainability picture. Secondly, as concern for environmental and social factors increases in sustainable supply chain management, a “wider set of performance objectives” is needed. Lastly, they see heightened need for “cooperation among partnering companies in sustainable supply chain management”. Seuring and Müller’s points all correlate to key points of this thesis and contemporary IE literature, but industrial ecology, eco-industrial networks, nor circular economy are referenced directly.

This literature in industrial ecology and supply chains has been shown to suggest increased scope and collaboration, and the structure of challenges ahead. Few examples are

given in either set of literature for what eco-industrial or circular economy planners should cooperate and collaborate on, and who should be collaborating. Some industrial ecology papers loosely suggest that firm managers hold the responsibility for coordinating, leading, and supporting collaboration (Paquin & Howard-Grenville, 2012). It should be clear that collaboration would initially span all operational functions and strategic objectives, with specific properties in each instance. Sarkis does provide a very broad a representation of the flows and boundaries for collaboration across supply networks (Sarkis, 2012). The flows he offers are Materials, Service, Financial, Information, and Waste, and the boundaries are Cultural, Economic, Informational, Legal, Organizational, Political, Proximal, Technological, and Temporal.

3.1.1 Firm/Network/Portfolio Decisions and Important Factors

The focus of sustainable supply chain literature typically takes the company viewpoint, or more often the network of all of the firms involved in supplying (and recovering) a product to (and from) its intended final user. Based on the literature it is rare that a single firm owns and controls decisions throughout the full supply chain. Yet a case study from China's Circular Economy unearths an example of an eco-industrial network within a single enterprise, the Guitang Group (Zhu, Lowe, Wei, & Barnes, 2007). The Guitang Group operates one of largest sugar refineries in China. Zhu et.al outline the efforts the Guitang Group to acquire and integrate downstream firms to create symbiotic connections that increase revenues, decrease environmental impacts, reduce disposal costs and improve product quality. Opportunities and challenges of industrial symbiosis design for full supply chains of individual firms is depicted. Could such an organization be both achieving sustainable economic, social and environment goals, while also violating anti-trust laws? This question provokes thought on the policy incentives and competition in sustainable supply chains. A firm may be faced with a strategic

choice of whether their supply chains should acquire upstream/downstream actors to create economic benefits and exert greater control, or whether they should choose instead to integrate their organization into multiple networks to increase flexibility, and social and economic stability.

The term integration is used frequently in supply chains texts, but with multiple and sometimes ambiguous meaning. The term Integrated Chain Management was coined in the Netherlands, and is defined by Seuring and Müller as “*supply chain management that takes environmental and social issues into account*” (Seuring & Müller, 2007). These authors explore the concept and report its increasing popularity in supply chains management. They identify ‘material and information flow’, ‘strategy and cooperation’ and ‘regional industrial network’ as three main tracks of development in integrated chain management.

A focus on integration is also evident in Circular Economy literature (Park J. , 2010). Park deepens the connection between some areas of industrial ecology and supply chain management investigated in this literature review.

Instead of a deep bibliometric analysis of supply chain terms, this chapter has given an intuitive summary of definitions and illustrations that convey important supply chain concepts related to eco-industrial networks. Three such terms create the “Triple-A Supply Chain” (Lee, 2004): “*Agility*”, the ability to respond to short-term changes in demand or supply quickly; “*Alignment*”, establishment of incentives for supply chain partners to improve performance of the entire chain; and “*Adaptability*”, the capability to adjust supply chain design to accommodate market changes.

These terms are immediately relevant to industrial ecosystem planning. Researchers at McKinsey & Co. support the importance of these terms in supply chains and sustainability

and advise a splintering of supply chains to decrease complexity (Malik, Niemeyer, & Ruwadi, 2011).

3.1.2 Supply Chain Risk and Resiliency

‘Triple-A Supply Chain’ elements all relate to Risk. The McKinsey report considers the future of risk to production networks. They advise “manufacturing networks” to hedge against risk, supporting the case that eco-industrial networks are key competitive advantages in future supply chain strategies (Malik, Niemeyer, & Ruwadi, 2011). Risk is a vital consideration in supply chain management. Disruptions along supply chains can greatly affect companies and society; resources may be prevented from reaching society, foods might spoil before reaching stores, or disruptions to component manufacture might leave products unfinished and unsold, causing losses or bankruptcy for firms. Severe disruptions are often unpreventable, and the mitigation of risks uneconomical (Pettit, Eiksel, & Croxton, 2010).

In keeping with the use of McKinsey & Co for private industry perspectives and trends, the following excerpt is borrowed from a 2011 report in relation to risk.

“The bottom line for would-be architects of manufacturing and supply chain strategies is a greater risk of making key decisions that become uneconomic as a result of forces beyond your control” (Malik, Niemeyer, & Ruwadi, 2011).

This notion appears often in supply chain research and IE literature. Supply chain managers and planners show concern about “lock-in” factors stemming from cooperative agreements like industrial symbiosis (Korhonen, 2004) (Boons & Berends, 2001). This is a significant hurdle for IE that will require quantitative and qualitative persuasion to overcome.

The Seuring/Müller sustainable supply chain management literature review found that prior to 2008 there were only two papers that carried the word ‘risk’ in the title (Seuring &

Müller, 2008). A shift in the focus of supply chain research occurred in 2008. A Google Scholar search for journals with “supply chain” in the title found 770 articles containing the words “sustainable supply chain risk” since 2009.

The discussions of risk and resiliency are relevant to the scenarios in this thesis. Risk is a crucial consideration for modern global supply chains. Cooperation and collaboration are again seen as important methods for risk reduction (Tang, 2006). Study of risks in supply chains and complex networks induces research on stability and resiliency (Ostrovsky, 2008) (Peck, 2005) (Peck, 2006).

Resilience is a term with origins in ecology, defined as “*the ability of a system to absorb changes and still persist, and distinguished from stability the ability of a system to return to an equilibrium state.*” (Holling, 1973) Resiliency studies make excellent examples for the bridging of paradigms between supply chain, industrial ecology, and ecology. Zhu and Ruth conducted sensitivity analyses of simulated removal of firms from industrial systems, under different formational and regulatory conditions. The study grants an understanding of resilience in industrial ecosystems (Zhu & Ruth, 2013). It finds that industrial ecosystems with high levels of dependency between actors are the most vulnerable to disruptions in supply or production. They find two crucial factors for risk mitigation and improved resiliency under disruption, and urge planners and facilitators to design networks for rapid expansion of many, low dependency connections and for adaptability.

Paquin and Howard-Grenville also reference resilience in industrial ecosystems in Europe. Successful examples of industrial symbiosis are able to thrive despite growth and contraction, addition and loss of member firms, and evolution of industries (Paquin & Howard-Grenville, 2012). Kilduff et.al discuss social network resilience, “*some have argued*

that all networks are only dynamically stable— that is, ties dissolve and form over time while the network as a whole continues” (Kilduff, Tsai, & Hanke, 2006).

This thesis considers risk and resiliency in the modeling approach for eco-industrial networks. However, robust testing of resiliency and decreased risk will not be fully addressed.

3.1.3 Reverse Logistics (RL) and closed loops supply chains

Reverse logistics (RL) provides a natural transition from supply chain research to the waste management and recycling review in this section. Reverse logistics is expressed as:

‘The process of planning, implementing, and controlling the efficient, cost-effective flow of raw materials, in-process inventory, finished goods and related information from the point of consumption to the point of origin for the purpose of recapturing value or proper disposal’ (Rogers & Tibben-Lembke, 2001)

RL can improve eco-efficiency by leveraging return flows of materials from markets and is another opportunity for competitive advantage. Firms are introducing innovative new business models that diverge from the linear flow model in which the sale of products drives revenue, to models in which services are provided to generate revenues. In this model firms maintain ownership of products and sell a service. Philips’ Illumination has is such a model. Philips sells a service providing companies with lighting and install and maintain lighting fixtures and instruments on the client’s premises to fulfill the service, but maintain ownership of the materials (van Houten, 2014). The concept has proven to be a strong competitive advantage for firms who have employed this model (Tukker & Tischner, 2006). A multitude of Reverse Logistics models for products and services span both supply chain and recycling/waste management topics (Spengler & Schröter, 2003) (Spengler, Püchert, Penkuhn, & Rentz, 1997). RL poses two big challenges for firms, ‘forecasting and acquisition of return flows’, and ‘ownership of materials and resources’ while at the end customer (Minner, 2001).

A feature on the circular economy emphasizes the need to incorporate reverse flows of resources in a ‘rounding of the supply chain’, and proposes strategies to achieve it (McKinsey & Company, 2012). McKinsey changed their vocabulary for supply chain in order to remove the linear connotation of chains. They coined the phrase “Supply Circle” in a publication titled “manufacturing resource productivity”, graphically represented in Figure 17. Supply Circle is a firm oriented concept that bridges this review of sustainable supply chains and reverse logistics, to waste management and recycling, and folds these topics conceptually together into what this thesis calls eco-industrial networks (Mohr, Somers, Swartz, & Vanthournout, 2012).

Figure 17 - The Supply Circle

McKinsey & Co. posits that organizations need to address four key areas, raw material sourcing, component production, product design, and return markets. The fourth bullet could

conceivably be title as reverse logistics or return supply, but this figure references the “market” as the focus for analysis and actions.

A Google Scholar search for “Supply Circle” only returned 26 articles with the term anywhere in the article, and zero results with Supply Circle in the title, implying that although this is a novel and logical concept, it has not gained traction in research.

3.2 Recycling and Waste Management

Waste management and recycling are intrinsic properties of sustainable supply chain research, and industrial ecology. The ecological and economic aspects of waste reduction and cycling underline much of chapter 2.

Google Scholar Search Terms	Term Found in Article	
	Anywhere	Title
Waste Management	2,310,000	52,600
Recycling OR Recycle	1,380,000	99,800
Waste AND “Industrial Ecology” OR “Industrial Symbiosis”	17,200	67
Recycling OR Recycle, AND “Industrial Ecology” OR “Industrial Symbiosis”	16,400	24
Waste AND “Supply chain”	70,000	108
Recycle OR Recycling, AND “Supply chain”	36,500	106

Figure 18 - Bibliometric Results for Waste Management and Recycling in Relation to Industrial Ecology or Industrial Symbiosis, and Supply Chain

The articles returned in searches for industrial ecology and industrial symbiosis with waste management or recycling are few, and the majority of these articles were specific to case studies. Combinations of these terms form narrow topics. The concepts may be better captured by different terminology from the larger aspects of supply chain and sustainability.

3.2.1 Recycling, Waste Management and Industrial Ecology

Spatial and resource constraints are strong motivators for sustainability movements. Forecasts for waste generation reinforce the necessity for change (Bruvoll & Ibenholt, 1997), and the need to decouple waste generation and economic growth (Sjöström & Östblom, 2010).

The global recycling industry has revenues of over USD 500 billion according to some estimates. Whether explicitly enrolled in definitions or not, recycling and waste management are core fundamentals of industrial ecosystems, noted by Liwarska-Bizukojc et.al *“It is essential for industrial ecosystems to have at least one industrial decomposer such as a recycling entity or network, and to create a symbiotic web among entities in the system”* (Liwarska-Bizukojc, Bizukojc, Marcinkowski, & Doniec, 2009), although Chertow provides a definition of industrial symbiosis in which recycling is not permitted to be the primary business of any of the firms involved (Chertow M. R., 2007). The two earliest examples of eco-industrial parks, Kalundborg and Styria were firstly considered examples of recycling networks (Schwarz, E.J. & Steininger, 1997). Styria is still deemed a recycling network, and a blueprint for many similar operations (Posch, 2010). Recycling is a central property of Urban Symbiosis (Ohnishi, Fujita, Xudong, & Fujii, 2012). The synonymous nature of recycling and industrial ecology is revealed by Geng & Cote. The function of recyclers and other byproduct consumers is related to ‘*scavengers and decomposers*’ in ecological systems (Geng & Cote, 2002).

Adam Minter provided an immersion into the operations and culture of the recycling industry in his 2013 book *Junkyard Planet*. He recounts his global travels as a journalist documenting the past three decades in the scrap, waste and recycling industry (Minter, 2013). His stories provide anecdotal evidence of risk and resiliency, using examples of fluctuating

commodity prices and their affect on secondary resources markets, and traders therein. He delivers an inside look at the collapse of international trade with Chinese recyclers of scrap following the market crash of 2008. The risks of both rising and fluctuating commodity prices are of prime concern for recyclers and waste managers (Kahhat, Kim, Xu, Allenby, Williams, & Zhang, 2008) (Pires, Martinho, & Chang, 2011) and supply chain professionals (Dobbs, Oppenheim, & Thompson, 2011).

Minter and multiple researchers all highlight local markets for collection and processing of wastes and recyclable materials, as central to recycling and waste management (Spengler, Ploog, & Schröter, 2003). However, they all note that it is the international flow of commodities through the global secondary market that create pricing and cost structures. Astute contributions to this international industrial ecosystem of recyclable flows were made by Donald Lyons (Lyons, Rice, & Wachal, 2009). He also relates developments in recycling and waste management to the supply chain theories (Lyons, 2005). His research analyzes spatial scale's implication to recycling networks in Texas. This thesis agrees with the findings that "loop closing" must be driven by markets, and has no standard geographic scale (Lyons, 2007). Lyons is credited for contributed to early industrial ecology and industrial symbiosis research, and other related discussions.

McKinsey offers an easily comprehensible conceptual overview of consumer products recycling and resource recovery operations from the firm based production and supply circle perspective in Figure 19.

Figure 19 - Looping resources back into the value chain through the Supply Circle (McKinsey & Company, 2012)

3.2.2 Legislation and Extended Producer Responsibility

This section returns to the “chicken or the egg” question referenced earlier in the debate between Boons and Desrochers, of whether the sustainable industry should be forged mainly through regulation and legislation, or market and environmental forces. Governments and governing bodies have the opportunity to engage, encourage or enforce sustainable development through policies with punitive measures or incentives.

Calcott and Walls question the relationship between waste disposal policies and impact on design through economic analysis (Calcott & Walls, 2000). They conclude that policy instruments (punitive or incentive based) cannot effectively encourage producers to alter

product design without fully functioning recycling markets. They cite deposit/refund programs as the exception to the rule, and advocate expansion of these programs.

It can be argued that waste management and recycling legislation *has* had a positive effect on eco-industrial network design and success. As detailed earlier the NISP program in the Britain has seen great success. It may not have gained such high traction with industry if waste management legislation had not taxed landfilled waste, or incentivized environmentally friendly practices (Mirata, 2004).

Particular policy attention has been paid to waste management in the electronics industry (e-waste), in both developed and developing countries (Saphores, Nixon, Ogunseitan, & Shapiro, 2005). The impact of disposal of e-waste is especially flagrant, and a significant problem in East Asia (Liu, Tanaka, & Matsui, 2006). In the European Union the Waste Electrical and Electronic Equipment (WEEE) directive was adopted in 2003, and updated in frequently through 2012. The directive set collection, recycling and recovery targets for electrical equipment (European Commission, 2014), and is analyzed in several articles. The impact of reaction and reaction to such legislation is seen predominantly within the product supply chain (Walther & Spengler, Impact of WEEE-directive on reverse logistics in Germany , 2005). This research goes on to explore the impact of WEEE legislation on waste recovery and recycling in detail. Walther and Spengler's model analyzes the financial and technical issues of the directive, and reveal opportunities for networks of recyclers to cooperate for increased capacity, efficiencies, and competitive advantage.

The WEEE directive deeply affected Extended Producer Responsibility (EPR), which is the responsibility of producers for end-of-life (EOL) products (Castell, Clift, & France, 2004). According to Castell et.al the WEEE directive and related Integrated Product Policy (IPP)

intended to overcome the economic deterrent for producers to take responsibility for EOL products. These laws and other waste management approaches in the EU are critically assessed and often criticized (Costa, Massard, & Agarwal, 2010). McDonough and Braungart agree in their book *The Upcycle*, stating legislation is “*the sign that redesign is required*” (McDonough & Braungart, 2013). In this case, the products, markets, and legislation all require redesign.

In addition to Government intervention, there are standardization tools that governing bodies can coordinate, such as the International Organization for Standards “ISO” criteria (International Organization for Standardization, 2014). Several volumes of standards are extremely effective in unifying common practices for design and operations through ISO codes in areas such as Quality Management (9000), Social Responsibility (26000), Energy Management (50001), Risk Management (31000), Food Safety (22000) and Information Security (27001). They also guide standards for Environment Management (ISO 14000) certifications and Sustainable Events (ISO 20121). These provide some current standardized best practices for eco-industrial design. Industrial ecology does not appear in these standards directly but some of the standards may aid implementation.

3.3 Synthesis of Fields and Considerations for Planning Approaches

Figure 20 - Evolution of Industrial Production Complexity (Haskins, 2007)

The definition of industrial symbiosis offered by Lombardi Et.al and the associated paper analyzing it in depth, serves to open the scope of industrial symbiosis (Lombardi & Laybourn, 2012). However, this literature review has shown that it is useful to open the scope of IS and IE further, to encompass the progress and ideologies of sustainable supply chain management, recycling, waste management and other related principles. A comprehensive solution to the challenges of sustainability must be devised through a facilitated multi-disciplinary, collaborative approach inclusive of all of the fields covered in this literature review, and must be underpinned by economic principles and realities, and supported by intelligent policy.

The references to increasing complexity in the global economic, production, consumption trends in this literature review provide insight into the difficulty of finding simple solutions through basic approaches. We have shown that there is value in our intention to infer planning principles through a mathematical modeling approach, as one data driven portion of planning and analysis of eco-industrial networks. This has been supported by evidence in the literature that it is possible to increase resiliency and stability and decrease risk for members of an eco-industrial network.

Beyond the Qualitative

In fairness to the failed US attempts to implement industrial ecology in the 1990's, the Fieldbook did cover many of the necessary factors to consider for planning and implementation (Lowe, Moran, & Holmes, 1996). It includes transportation and logistics, recycling, reuse and remanufacturing, and waste management and at one point, references supply chain. However, it may be that the data, tools, technology, and expertise were not available at that time. A more comprehensive understanding of the scale of project planning and management required has now been established, and many more technologies and data are available today. This thesis shows that each of these respective fields have progressed in very similar directions regarding sustainable development.

There are opportunities to drive sustainable development by employing technology advancements in computing and 'Big Data' analytics. Mathematical models and simulations can provide cost-effective insight for planning and management solutions for industrial ecosystems. These tools are increasingly valuable in practical applications of circular economy and eco-industrial networks. However, as with all modeling methods, the tools and information currently available are unable to comprehensively capture every economic, social, environmental and technical aspect of complex real-world systems. Modeling must not be the sole method used in planning. The 'noncomputable' ought be accounted for qualitatively (Carpenter, Folke, Scheffer, & Westley, 2009). The models in this thesis are offered for use with pragmatic reasoning, in conjunction with other tools in an inclusive and holistic approach to planning.

CHAPTER 4 – REVIEW OF MODELING APPROACHES

The previous chapters showed the interconnectedness of research fields, which is reinforced in this chapter by recurring modeling themes found in each field.

The literature search for network modeling approaches involved scholarly database searches for modeling review papers in the fields of industrial ecology, sustainable supply chain management and recycling and waste management. The most significant findings from reviews in each field are summarized, and network optimization approaches relevant to this thesis are reviewed.

Industrial Ecology – Chemistry & Ecology Modeling

The Industrial Symbiosis classification outlined in Chapter 2, has a focused scope on the symbiotic technical connections between firms. Consequently this class of industrial ecology is rooted in chemistry and relates to environmental ecological processes. An international collaboration between academic-corporate researchers produced an article reviewing all of the modeling techniques used for industrial symbiosis, with a focus on industrial processes, especially chemical processes (Gondkar, Sreeramagiri, & Zondervan, 2012). The authors group the modeling approaches into assessment and optimization approaches. All referenced optimization approaches address already existing systems, so likely relate only to scenario two of this thesis. All of these process oriented optimization approaches require great level of detail for processes, materials and methods. The types of models range from complex deterministic approaches, to genetic algorithms and neural networks.

The article includes an assessment of environmental performance indicators, such as life cycle analysis (LCA), as they relate to industrial ecosystems. LCA has a strong influence on

policy and management, but cannot capture the full impact of a system. Reasons cited are incomplete economic or environmental accounting for ecological products and processes, and overly standardized databases that may not capture new techniques or dependencies in streams. Contrastingly, frequently used input-output analyses, can capture economic flows or material and energy flows for impact analysis. Ecological Input-Output Analysis (EIOA) is used to analyze all three aspects of sustainability, tracing economic, and material and energy flows, and societal behavior for industrial ecosystems. Optimization difficulties shared by both of these techniques come from the tremendous data requirements. Models proposed for this thesis shall require minimal information from firms, and thus would not consider these approaches.

Gondkar et.al's conclusions follow the pattern from the reviews in earlier chapters, that for effective optimization and planning, boundaries must be expanded to consider the full systems. They also stress the complexity this causes, and major resulting difficulties for modeling industrial ecosystems. They end the review by expressing that the current state-of-the-art in industrial ecology modeling is in Robust Optimization. These models are complex, stochastic, multi-objective, often modular optimization problems that at once address the deepest technical levels of industrial symbioses, and the full complexity of the whole network. They aim to minimize environmental impact and health and safety risks, maximize economic performance, and minimize supply chain risks such as facility disruptions and input shortages. The authors offer a three level modular framework for robust optimization. Their model optimizes at the lowest technical and temporal level of titled "process floor/control", then the middle, "short term scheduling" level, and finally optimizes at the "long term planning", network level. Each level provides information to the next level, and receive decisions and constraints as feedback for iterative optimizations. Again, the information required is massive.

The broadening of modeling approaches seen in industrial ecology shows a progression towards supply chain considerations. Supply chain modeling is reviewed in the next section.

Supply Chain and Reverse Logistics

Seuring published a 2013 article reviewing quantitative modeling approaches (Seuring, 2013), which from a sample of 309 papers on sustainable supply chain management, selects the 36 deemed as quantitative modeling articles, for reviewed. Two additional reviews are used for a well rounded approach to reviewing supply chain modeling. A Facility Location and Supply Chain modeling review (Melo, Nickel, & Saldanha-da-Gama, 2009), and an Environmentally Conscious Manufacturing and Product Recovery, or “ECMPRO” review (Ilgin & Gupta, 2010).

Seuring’s review groups papers into four modeling techniques, and by sustainability goal relations. The four divisions of the modeling approaches are, in order of quantity of papers of each type in the literature review:

- Life-cycle assessment, *“assessing environmental impacts along a supply chain and minimizing them”*
- Equilibrium models, *“balancing environmental and economic factors and finding and equilibrium or optimal solution”*
- Multi-criteria decision making, *“optimization of economic and environmental criteria, usually balancing trade-offs or identifying optimal solutions”*
- Analytical hierarchy process, *“structuring a decision process thereby obtaining aa solution based on semi-quantitative criteria and respective weights”*

The article also analyzes the percentage of goal relationship types across the three elements of sustainability (social; environmental; economic) for all sustainable supply chain research. The analysis shows that of all papers 53% find “win-win” situations, but only 19% of modeling papers supported a positive relationship between environmental and social sustainability factors, and economic objectives. Modeling papers showed that 56% of cases showed trade-offs, as opposed to only 31% of total papers found tradeoffs between environmental considerations and economic success. The remaining 16% of all papers, and 25% of modeling papers find minimum performance for environmental and social issues.

Melo et.al build a comprehensive review of supply chain and facility location modeling approaches by type, with increasing complexity as the supply chain structure incorporates more features (Melo, Nickel, & Saldanha-da-Gama, 2009). Location models have a particular connection to the scenarios in this thesis, as both scenarios consider already existing firms that have already established locations. Thus the decisions for inclusion in new or existing eco-industrial networks will consider location as a factor.

Melo et.al begin with the most basic ‘location-allocation’ structures, and class models by single period and multi-period planning horizons, and by deterministic and stochastic approaches. The next level of the review are models assessing decisions for other supply chain problems within the simple structure, including capacity, inventory, procurement, production, routing and transportation modes. Reverse logistics models in relation to supply chain are classed by network structure (recovery or closed loop), and by facilities supporting activities (collection and/or rework). Finally, the review covers models considering additional features of facility location models, spread across Financial aspects (International factors; incentives; budget constraints), Risk Management (robustness; reliability; risk pooling), and other aspects including relocation, bill of materials, and multi-period factors.

A critical outcome of the Melo et.al review is the dominant role of cost related measurements in supply chain modeling. A statistical analysis of the performance measures used in supply chain modeling, and the methods of solution is conducted. The authors find that 75% of models aimed to minimize costs, while only 16% aimed to maximize profit, and 9% considered multiple and conflicting objectives such as environmental measurement. For solution methods, 45% used a specific algorithm providing a heuristic solution, 30 used a specific algorithm granting an exact solution, 23% used a general solver with an exact solution, and 2% used a general solver for a heuristic solution.

Quantitative assessment and modeling approaches have been developed in each of the fields in the review. Tools most frequently used to calculate environmental factors are material flow analysis, used to study industrial metabolisms and technical nutrient flows through industrial processes and networks; forms of life cycle assessment, for design, assessment, and calculation of environmental footprints for products, services and organizations; and environmentally extended input-output analyses to assess the economic and environmental interdependencies within a system.

Ilgin and Gupta depict the categories of research that link the fields of supply chain and reverse logistics, with recycling and waste management Figure 21 in which mathematical modeling is applied (Ilgin & Gupta, 2010).

Figure 21 - Environmentally Conscious Manufacturing & Product Recovery Review (Ilgin & Gupta, 2010)

Recycling & Waste Management

Several modeling approaches have been applied to recycling and waste management networks. Some of these models are useful for eco-industrial network design. One approach in particular deals with the aspect of collaboration, which was considered an essential part of future research in each section of the literature reviews in Chapters 2 and 3 above. Walther, Schmid, and Spengler modeled negotiation-based coordination for recycling networks, for increased scale and mutual competitive advantage of members (Walther, Schmid, & Spengler, 2008).

Recovery methods for products, materials and energy from end user markets are an essential component of sustainable economies. This thesis will not explore the actual methods

of recovery, but the model will be extended to incorporate the flows of recovered materials back into the production cycle.

Modeling in This Thesis

The scenarios for the modeling in this thesis have been clearly stated. An objective of this thesis is development of a decision model requiring minimal information from firms. Thus, simplicity is an implied requirement.

The Transportation Problem is deemed the simplest type of model for potential use in eco-industrial network design and management for this thesis. This is a classic theory that extends back to 1781 when it was first formalized, and was solved mathematically in the 1920's, before the theory and solution methods matured during World War II (Schrijver, 2002). This basic optimization model comprises several sources with fixed supply levels, and several destinations with fixed demand. The objective is to minimize transportation cost, or maximize profit. This model will be extended to solve both scenarios in the next chapter.

CHAPTER 5 – MODELING ECO-INDUSTRIAL NETWORKS

A comprehensive review of industrial ecology has been presented, and both idealistic/theoretical and realist/practical perspectives have been portrayed of industrial ecology and related fields. The section above reviewed modeling approaches to planning and operations in the literature of fields review. This chapter will follow the methodology outlined in the introduction, including problem formulation, assumptions, and model formulations and solutions, and analysis of results, and discussion of the two model solutions. A discussion on these theoretical models and their feasibility and implications for planning and managing eco-industrial networks concludes the chapter.

5.1 Scenarios and Problem Formulation

The two basic problem statements this thesis aims to solve are as follows:

- Problem 1 – No coordinated network yet exists. The goal is to develop a model to provide solutions that can be used for insight into planning a centrally facilitated and planned eco-industrial network.
- Problem 2 – An industrial or eco-industrial network already exists. The task here is to develop a model to provide solutions that can be used for insight into the managed improvement of a facilitated eco-industrial network by adding or removing member firms.

The scope of these problems is intended to be narrow. It is clear from the literature review that there are many stages and many technical, social and policy challenges to be considered when planning any form of eco-industrial network. This complexity is recognized in this thesis but not accounted for in the simple models. The scope of the models is narrowed

by the introduction of several assumptions used to generate initial conditions and information, necessary to develop and solve the models.

Figure 22 - Pre-Requisite Assumptions to Generate Scenarios

5.2 Assumptions

Figure 22 gives an indication of the pre-requisite stages, conditions and assumptions necessary to reach the point where the models developed in this thesis apply. The assumptions are detailed in this section.

Initial Conditions Assumption

The first assumption is that firms and industries have previously realized all readily achieved economic opportunities and efficiencies; act on market forces and within their regulatory framework; and are in a state of relative competitive and economic equilibrium. In Figure 22, the left-most arrow represents forces that affect this balance, creating opportunities and/or challenges that motivate firms to alter operations and/or strategies.

5.2.1 Pre-Requisite Stages

Motivation Stage

In order to establish the motivation or need for change, it is assumed that a development occurs in at least one of four factors found in the literature review to be most significant in affecting change. It is assumed also that firms act rationally and in their own best interest to explore and pursue revenue and brand opportunities to gain competitive advantage, to mitigate risks, to react to unforeseen events and/or prepare for forecasted events, and to transcend challenges as they arise. Seuring and Müller describe these as “triggers” as seen in **Error! Reference source not found.** The four factors (pressures or incentives) are outlined below.

Four Factors Affecting Change

Regulatory Impact – Governments or regulators pass and/or enact new legislation. This affects the operations of a firm by increasing costs and/or decreasing revenues, or creates opportunities for new revenues and/or decreased costs. An example is an international treaty such as the famous Kyoto Protocol (UNFCCC). Opportunities increased for firms offering low-carbon solutions, and costs were increased for countries and consequently organizations with high carbon footprints.

Technological Advance –Research and Development (R&D) is invested in by firms, governments, academic institutions, and non-governmental organizations. A certain pace of development exists in the relative equilibrium mentioned in the introduction to this section. The increasing pace of innovation perpetuates the need for continued R&D for firms to gain or maintain competitive advantages. This increasing pace means increasing frequency of “game-changing” innovations that alter the competitive landscape for firms offering products and

services. These innovations were seen in every era of history from cavemen's manipulation of fire, through the industrial revolution to the age of the Internet (Graedel & Allenby, 2010).

Market demands – The consumer marketplace is continually evolving. A shift in the demand in the market for a certain type of goods or service can be the result of cultural changes, societal needs or wants, or as more information becomes available regarding any of the other three factors mentioned here.

Environmental Influence – Whether through a gradual change or rapid shift, environmental factors are implied in the literature review to affect all of the three factors above. The influence to firms may result from, but are not limited to, resource availability/cost; climate change and its effects on consumer perceptions and/or government legislation; natural disasters and their effects on supply chains/circles or purchasing power in markets; or spread of a disease that punishes the lack of biodiversity in monoculture of crops, affecting agricultural yield agricultural yield; or any other such topic outlined at the Rio+20 Summit for Sustainable Development.

The variables mentioned each category are not exhaustive, but are representative of the types of influences to firms within each factor topic.

Network Availability

Once an opportunity or challenge arises, the facilitating and coordinating organization can be present to begin collaborating with firms. The stage of Cooperative Willingness is a decision stage for firms. This stage assumes that firms choose either to accept advice and open up to network collaboration, or choose to pursue competitive advantages without network collaboration.

Information Availability

“A critical element in cross-sector collaboration at scale is insight into how material flows of two entirely different value chains may be of relevance to each other. This starts with sufficient information on what waste or by-product streams are available” (Ellen MacArthur Foundation, 2013).

Considerable and often proprietary information may be required in real-world settings. It is assumed that the necessary information is known, or can be learned by a firm. It is also assumed that social and political skills, honesty and openness are present in industrial firms and with any facilitating actor involved in the network, so that the necessary information is shared with the facilitating body. This assumption negates many social, trust-based issues arising in the review.

For simple illustration of the solution methods for the problems outlined, the model in this thesis deliberately limits the information that is required from each firm. We only require the data on material transformation from inputs to outputs for each recipe a firm can utilize in production, and can be revealed with little loss of proprietary information.

Feasibility Stage

This stage references factors illustrated in the literature review. Each firm may choose to be available to eco-industrial network inclusion. This allows a facilitating organization to explore connections available to the firm. In the case of this thesis, the exploration is based on the technological coefficients and volumes of inputs and outputs. Input-output matching alone has proven insufficient in several previous case examples (Chertow, Portlock, & Coppock, 2002) (Chertow M. R., 2000) (Heeres, Vermeulen, & de Walle, 2004). The reasons are many, but input-output matching remains a necessary component of eco-industrial development.

To reach the point where simple models can be developed and solved, this section assumes the following feasibility tests are passed for firms that agree to network collaboration.

Technological Feasibility: Physical testing for matching inputs and outputs. Can the exchanges and transformations technically or chemically take place? Can the material be shipped safely? Is any setup cost feasible? Is the quality and available quantity correct or at least acceptable?

Economic Feasibility – Market Test. Does it make economic sense to stakeholders... does it reduce cost, increase quality, reduce waste, mitigate risks, shorten the supply chain/circle?

Portfolio Feasibility – Corporate Test. Does the activity fit into the corporate strategy and mission statement? Does collaboration with suppliers and or sale of by-products to other producers fit with business portfolio? Does dealing with these other firms or entering the eco-industrial network improve brand image?

Other Considerations

This section was a summary of considerations to lend clarity to the assumptions made prior to the model development in the next section.

The main qualifier for an eco-industrial network will be related to Chertow's conditions for industrial symbiosis to "*focuses on predominantly commercial and industrial activities that include a materials exchange component to qualify the activity as industrial symbiosis.*" (Chertow & Ehrenfeld, Organizing Self-Organizing Systems: Toward a Theory of Industrial Symbiosis , 2012).

In reality, additional dimensions of life cycle analysis or material flow analysis might be used to quantify analyze the impact of full product cycles, from mining, manufacture, use, post-use recovery, and end of life. Another consideration is that a consistently changing industrial network may also incur both financial and environmental “setup costs”. A prudent designer would also consider these factors as part of the technological implications of adding, or removing a firm or process to or from the network. However, this will not feature in this thesis’ model.

Firms react to the forces in Figure 22 and are assumed to follow the feasibility testing illustrated. The eco-industrial network planning and management decisions must consider similar factors when deciding which firms to include, or maintain in the network. The network planners will consider short and long-term financial aspects (economic trends), employment levels, public opinion and social issues discussed in the literature review (society), government policies and incentives, and environmental factors. Technology can be influential within each of these factors. The dimensions and directions of these influences are presented in Figure 23.

Figure 23 - Eco-Industrial Network Planning and Management Policy Dimensions for Selection of Members from Interested Firms

5.3 Model Formulation

The figure below provides a conceptual overview of an eco-industrial network including a set of available supplies, a set of producers willing to collaborate in the network; a set of markets with demands for products; and a set of arcs between nodes. The arcs are paths of material flows.

Figure 24 - Conceptual Overview of Eco-Industrial Network

Supply Constraint (S_l) and Material Flows of External Suppliers

The sum total of material X_{lm} supplied from each supplier l to each producer m in the set of producers M cannot exceed total quantity of available supply S_l . This constraint is represented conceptually in the figure below

Figure 25 - External Supply Constraint

This constraint is represented algebraically as:

$$\sum_{m=1}^M X_{lm} \leq S_l \quad \forall l \quad (2)$$

Purpose: this constraint is indicative of the theme of resource scarcity illustrated throughout the literature review. This constraint conceptually represents raw materials mined and processed from the natural environment, but in case examples this may not be a natural resource. Altering this constraint may allow some simulation of environmental trends and a test for the model's behavior and reaction.

Demand Constraint and Material Flows For Products to Markets

The sum total of outputs Z_{mn} received by external market node n from the set of producers M must equal or exceed demand D_n at external market node n . This constraint is represented conceptually in the figure below

Figure 26 - Demand Must Be Met or Exceeded Constraint

This constraint is represented algebraically below

$$\sum_m^M Z_{mn} \geq D_n \quad \forall n \quad (3)$$

Purpose: Market demands are necessary in market economies. Demand creates a pull-based system in order to meet the demand. In this simple model, it is a final demand, but it is recognized that post-final-user recovery, recycling/refurbishing would take place in a complete eco-industrial network or circular economy.

Material Input and Output Flows Through Producers

Inputs l flow to producer in the amount X_{lm} from the set of external suppliers L . Inputs of type l and volume $Y_{lm'm}$ also flow to m from the other producers m' . The inputs are materially transformed into outputs in ratios of technical coefficients of recipes r_m . Two types of outputs may be produced by producer m : Product Outputs n with volume Z_{mn} that flows from producer m to the market for product n ; and by-products of type l with volume $Y_{lmm'}$ that flow from m to the other producers m' . The flows of inputs and outputs for a producer are represented conceptually in the figure below.

Figure 27 - Material Input and Output Flows for Producer m

Three Material Transformation Constraints for Producer Nodes

Technical coefficients are required to develop transformation equations are required for each producer m in order to the transform inputs l into output products Z_{mn} to meet market demand for n , and by-product outputs Y_{lmm}' available to other producers m' as inputs.

To represent these transformations we use a set of recipes $R, \{1 \dots R\}$. Each recipe r_m is represented by the ratio of inputs to outputs. The technical coefficients for inputs required in each recipe are represented by a subset of Inputs $a_{r,l}, \{a_{l,1} \dots a_{R,L}\}$. The outputs created by a recipe are represented by a subset of outputs $b_{r,n}, \{b_{l,1} \dots b_{R,N}\}$ and by-products $b_{r,l}, \{b_{l,1} \dots b_{R,L}\}$. A scalar $h_{r,m}$ is used to represent the production level of a recipe where a production level of one ($1_{r,m}$) is equal to the basic ratio of inputs to outputs for recipe r_m . A production level of two ($2_{r,m}$) would require twice the volume of inputs a_l and create twice the volume outputs $b_{r,n}$ and $b_{r,l}$ represented in the technical coefficients for inputs to outputs for recipe r_m . A binary array $rm_{r,m}$ is used to represent the ability or inability of each producer m to use each recipe r_m .

The transformation for each recipe r_m used by producer m at production level $h_{r,m}$ is represented conceptually in the figure below.

Figure 28 - Conceptual Representation of Technical Coefficients for Recipe

Use of All Inputs in Recipes Constraint

Simple definition: For all inputs and producers, all inputs received by a producer must be used in recipes in that producer.

Extended definition: For all inputs L and producers M , the total amount of material l received at producer node m from raw input supplier l plus the total amount of by-product flow of inputs $Y_{lm'm}$ received from all other producers M' must be equal to the sum total amount of all materials of type l required in recipes r_m used at operating rates $h_{r,m}$, for all recipes that are used $rm_{r,m}$ at producer m .

This constraint is represented algebraically below

$$X_{lm} + \sum_{m'=1}^M Y_{lm'm} = \sum_{r=1}^R h_{r,m} a_{r,l} rm_{r,m} \quad \forall l, m \quad (4)$$

Purpose: This constraint ensures that producers only buy or receive inputs that are required by recipes that they will use.

Flow of All Product Outputs to Market Constraint

Simple definition: For all producers and markets, the product outputs produced must flow to markets.

Extended definition: For all producers and external demand markets, the total amount of product output of type n produced by node m using recipe r_m at rate $h_{r,m}$, for all recipes used at that producer $rm_{r,m}$, must be equal to the amount of output flows Z_{mn} from producer m to each external demand market node n .

This constraint is represented algebraically below

$$\sum_{r=1}^R h_{r,m} b_{r,n} rm_{r,m} = Z_{mn} \quad \forall m, n \quad (5)$$

Purpose: This constraint ensures no product outputs build up at producers as waste. This assumes all products will be accepted or bought by markets.

By-product Build-up as Waste Constraint

Simple definition: For all inputs and producers, a greater or equal amount of by-products must be made by a producer than the amount shipped to other producers to be used as inputs in recipes and the amount reused at the same producer.

Extended definition: For all inputs of type l and producers m , the sum total of by-product outputs of type l produced in recipe r_m at rate $h_{r,m}$ for all recipes used at that producer $rm_{r,m}$

must be equal or greater than to the sum amount of by-product flow $Y_{lmm'}$ from m to m' which includes by-product reused by m .

This constraint is expressed algebraically below

$$\sum_{r=1}^R h_{r,m} b_{r,l} r m_{r,m} \geq \sum_{m'=1}^M Y_{lmm'} \quad \forall l, m \quad (6)$$

Purpose: This constraint maintains a material balance by preventing shipping of by-products that haven't been produced. The inequality of the constraint allows by-products Y_l to be produced and not used, thus reflecting a by-product becoming a waste. This is an important component of the model, as it reflects the reality of a typical “non-eco” industrial park that does not consider the economic or environmental cost of production waste. The inequality allows firm to dump by-products if it is an economically superior option to shipping them to other producers. This constraint can be adjusted for the scenarios in later iterations of this model.

Network Objective –Cost Minimization

Objective Function minimizing cost (f):

$$\text{Minimize } f = \sum_{l=1}^L \sum_{m=1}^M cx_{lm}X_{lm} + \sum_{l=1}^L \sum_{m=1}^M \sum_{m'=1}^M cy_{lmm'}Y_{lmm'} + \sum_{m=1}^M \sum_{n=1}^N cz_{mn}Z_{mn} \quad (7)$$

Subject To⁴:

$$\sum_{m=1}^M X_{lm} \leq S_l \quad \forall l \quad (8)$$

$$\sum_{m=1}^M Z_{mn} \geq D_n \quad \forall n \quad (9)$$

$$X_{lm} + \sum_{m'=1}^M Y_{lm'm} = \sum_{r=1}^R h_{r,m} a_{r,l} r m_{r,m} \quad \forall l, m \quad (10)$$

$$\sum_{r=1}^R h_{r,m} b_{r,n} r m_{r,m} = Z_{mn} \quad \forall m, n \quad (11)$$

$$\sum_{r=1}^R h_{r,m} b_{r,l} r m_{r,m} \geq \sum_{m'=1}^M Y_{lmm'} \quad \forall l, m \quad (12)$$

$$X \geq 0, \quad Z \geq 0, \quad Y \geq 0, \quad h_{r,m} \geq 0 \quad (13)$$

⁴ Full algebraic notation for the constraint equations can be viewed in the appendix

5.4 Quantitative Example

In order to test the model we require the technical coefficients for recipes and facility locations for firms⁵. We must also create additional corresponding notation⁶:

- Recipe transformations:
 - Required inputs a_l
 - Corresponding outputs b_n and b_l
- Recipes used at each producer ($rm_{r,m}$)
- Cost calculations: Notation, Data and Equations
- Weighting factors for transportation of different materials:
 - Weighted value of inputs and by-product outputs of type l (w_l)
 - Weighted value of product outputs of type n (w_n)
- Length of arcs (acceptable transportation paths between nodes):
 - Distance from suppliers l to producers m (dx_{lm})
 - Distance from producers m to other producers m' ($dy_{mm'}$)
 - Distance from producers m to markets n (dz_{mn})
- Calculations
 - Cost per unit from external supplier l to producer node m (cx_{lm})
 - Cost per unit from producer node m to producer node m' ($cy_{mm'}$)
 - Cost per unit from Producer node m to demand node n (cz_{mn})
- Cost Coefficients
- Supply Limits (S_l)
- Demand Thresholds (D_n)

⁵ All recipes and their corresponding vectors of technical coefficients are arbitrary values used for the sake of testing the model's feasibility. These values are not representative of any particular materials, processes, industries or case studies reviewed.

⁶ For ease of interpretation and notation in this example, the set of N , $\{1, 2, 3, 4, 5\}$ will be substituted for N , $\{\alpha, \beta, \gamma, \delta, \epsilon\}$. This will not be reflected in the programming language used with the GAMS software

Recipe Transformations –Required Inputs

The table below shows each vector of input coefficients for recipes a_{rl} which represent the number of units of each input required for a recipe r_m . (These values are entirely arbitrary)

Table 8 – a_{rl} Technological coefficients for inputs of type l required in recipe r_m

Recipes	Inputs			
	A	B	C	D
Recipe 1	4	5	0	0
Recipe 2	0	3	1.5	0
Recipe 3	1	0	0	4
Recipe 4	3.5	5.5	0	0
Recipe 5	0	0	1	2
Recipe 6	0	0	2	6
Recipe 7	0.5	0	1	0

Below is an algebraic representation of the recipe input coefficients (a_l):

$$\begin{aligned}
 a_1 &= 4A + 5B \\
 a_2 &= 3B + 1.5C \\
 a_3 &= A + 4D \\
 a_4 &= 3.5A + 5.5B \\
 a_5 &= C + 2D \\
 a_6 &= 2C + 6D \\
 a_7 &= C + .5A
 \end{aligned}$$

Recipe Transformations – Corresponding Product Outputs (b_n)

Table 9 – $b_{z,m}$ Product output coefficients of type n produced by recipe r_m

Recipes	Product Outputs				
	α	β	γ	δ	ϵ
Recipe 1	1	0	0	0	0
Recipe 2	0	4.2	0	0	0
Recipe 3	0	0	3	0	0
Recipe 4	1.8	0	0	0	0
Recipe 5	0	1	0	2	0
Recipe 6	0	0	0.5	1.5	0
Recipe 7	0	0	0	0.5	0.5

An algebraic representation of the recipe product outputs (b_n) is shown below:

$$b_1 = 1\alpha$$

$$b_2 = 4.2\beta$$

$$b_3 = 3\gamma$$

$$b_4 = 1.8\alpha$$

$$b_5 = \beta + 2\delta$$

$$b_6 = 1.5\delta + .5\gamma$$

$$b_7 = .5\delta + .5\epsilon$$

Table 10 – $by_{r,l}$ technological coefficient for by-product outputs of type l produced by recipe r_m

Recipes	Inputs			
	A	B	C	D
Recipe 1	0	0	0	2
Recipe 2	0	0	0	1.5
Recipe 3	0	0	0	0
Recipe 4	0	0	2	0
Recipe 5	0	0	0.5	0
Recipe 6	0	2	0	0
Recipe 7	0	1	0	0

Recipe Transformations – Corresponding by-product output coefficients ($b_{r,l}$)

An algebraic representation of the recipe by-product outputs ($b_{r,l}$) is shown below:

$$\begin{aligned}
 b_1 &= 2D \\
 b_2 &= 1.5D \\
 b_3 &= N/A \\
 b_4 &= 2C \\
 b_5 &= .5C \\
 b_6 &= 2B \\
 b_7 &= B
 \end{aligned}$$

Recipe Used at Each Producer

Figure 29 – Conceptual view of recipes available in producer in this example ($rm_{r,m}$)

The conceptual overview in the figure above illustrates the availability of recipes to each producer. Producer 1 has the technology and the capability available to use recipe 1 and/or recipe 2 in production; Producer 2 can use recipe 3, 4 or 5 in production; and Producer 3 can utilize recipe 6 or 7.

The binary array rm_{rm} representing the recipes available to each producer is shown in the table below.

Table 11 – rm_{rm} : Binary array of recipes used at producer m

rm_{rm}	Producer 1	Producer 2	Producer 3
Recipe 1	1	0	0
Recipe 2	1	0	0
Recipe 3	0	1	0
Recipe 4	0	1	0
Recipe 5	0	1	0
Recipe 6	0	0	1
Recipe 7	0	0	1

A summary of the transformational ratios of inputs to outputs for each recipe and corresponding producer r_m is represented in the table below.

Table 12 – Summary recipe transformations for each recipe in the example

Recipe r_m		Inputs	Outputs
1_1	$\rightarrow$	$4A + 5B$	$= (1\alpha) + (2D)$
2_1	$\rightarrow$	$3B + 1.5C$	$= (4.2\beta) + (1.5D)$
3_2	$\rightarrow$	$A + 4D$	$= (3\gamma)$
4_2	$\rightarrow$	$3.5A + 5.5B$	$= (1.8\alpha) + 2C$
5_2	$\rightarrow$	$B + 2D$	$= (\beta + 2\delta) + .5C$
6_2	$\rightarrow$	$2C + 6D$	$= (1.5\delta + .5\gamma) + 2B$
7_2	$\rightarrow$	$C + .5A$	$= (.5\delta + .5\epsilon) + B$

Cost Coefficients and Equations

Notation

dx_{lm} Distance between supplier l and producer m

$dy_{mm'}$ Distance between producer m and producer m'

dz_{mn} Distance between producer m and market n

wi_l Weighted cost for shipping input l

wo_n Weighted costs for shipping output n

c_{lm} Cost per unit flow of from External Supplier l to Producer Node m

$c_{lmm'}$ Cost per unit flow from Producer Node m to Producer Node m'

c_{mn} Cost per unit flow from Producer Node m to External Demand Node n

Weighted Costs of Inputs wi_l

$$W_1 = 1$$

$$W_2 = 1$$

$$W_3 = 1$$

$$W_4 = 1$$

Weighted Costs of Outputs wo_n

$$W_1 = 1$$

$$W_2 = 1$$

$$W_3 = 1$$

$$W_4 = 1$$

$$W_5 = 1$$

Lengths of arcs (distances between nodes in miles)

Table 13 – dx_{lm} Distance l to m

dx_{lm}	Producers (m)		
	1	2	3
Supply Nodes			
A	2	2	2
B	2	2	2
C	2	2	2
D	2	2	2

Table 14 – $dy_{mm'}$ Distance m to m'

$dy_{mm'}$	Producers (m')		
	1	2	3
Producers (m)			
1	0	2	2
2	2	0	2
3	2	2	0

Table 15 – dz_{mn} Distance m to n

dz_{mn}	Product Markets (n)				
	α	β	γ	δ	ϵ
Producer (m)					
1	2	2	2	2	2
2	2	2	2	2	2
3	2	2	2	2	2

Cost per unit flow

Unit cost of material l shipped from l to m is calculated by multiplying the distance from l to m and the weighted cost for shipping material l :

$$c_{lm} = d_{lm}wi_l \quad (14)$$

Cost of shipment of material l from m to m' is calculated by multiplying the distance from m to m' by the weighted cost for shipping material l :

$$c_{mm'} = d_{mm'}wi_l \quad (15)$$

Cost of shipment of material n shipped from m to n is calculated by multiplying the distance from m to n by the weighted cost for shipping material n :

$$c_{mn} = d_{mn}wo_n \quad (16)$$

Constraint Values

For model testing, all weights and distances shall be equal. The results should indicate that cost of transportation is not yet a factor in material sourcing decisions.

Demand Thresholds:

Demand thresholds in this example are again equal as the model is tested. Demands will initially be very low in comparison to supply constraints in order to provide the best opportunity for a feasible solution.

$D_1 = 500$ units	Alternative Notation $D\alpha$
$D_2 = 500$ units	Alternative Notation $D\beta$
$D_3 = 500$ units	Alternative Notation $D\gamma$
$D_4 = 500$ units	Alternative Notation $D\delta$
$D_5 = 500$ units	Alternative Notation $D\epsilon$

Supply Limits (S_l):

External supply is set at a very high level in order to avoid an infeasibility.

$$\begin{aligned} S_A &= 30000 \text{ units} \\ S_B &= 30000 \text{ units} \\ S_C &= 30000 \text{ units} \\ S_D &= 30000 \text{ units} \end{aligned}$$

Test Model Analysis

The test model was coded and programmed into the GAMS modeling software. The input code and the output of results can be viewed for the test in the Appendix. The model provides a feasible solution for minimizing cost f . The equations used by the software match full algebra provided in the Appendix. The model shows marginal values that show the model works as intended.

5.6 Problem 1

Problem Statement 1 – No coordinated network yet exists. Develop a model to provide solutions that can be used for insight into planning a centrally facilitated and planned eco-industrial network.

Formulation

The first scenario is tested by entering values for the distances between nodes that approximately represent the spatial distances of the network in figure 24.

Weightings of input materials are arbitrarily changed to weights ascending in equal increments from A with the least impactful weighting of 4, to D as the most impactful weighting of 7. Weightings for products with market demand remain unchanged⁷. Supply is decreased to 2000 units for all inputs to increase the likelihood of supply limits becoming a factor in by-product material exchange. The recipe transformations and demand thresholds remain the same as in the original model.

Solution

The problem 1 optimization indicates which firms are included in the network (those with at least one recipe of a firm has a production level greater than zero). The solution to this problem is illustrated in the figure below. All input supply nodes are used. All producers are selected to be a part of the network. All demands are met by only one producer. All producers are linked by by-product output flows. However, producer 1 does not supply producer 3 any by-products.

⁷ It is recognized that this implies an unrealistic lack of economic disincentive for overproduction which exceeds market demand. We assume all products will be sold. The model can be extended to incorporate this but it is beyond the scope of this thesis.

The input code and full output of results can again be seen in the Appendix. The significant results for Problem 1 can be seen in table 16.

Figure 30 - Conceptual Representation of Problem 1 Solution

Table 16 – Summary of significant output information from Problem 1

Total network cost f	\$133,829.37				
Raw (external) inputs used in recipes X_{lm}	A	B	C	D	
	1639	885	623	488	
Firms in the network m	1		2		3
Recipes utilized r_m	2	3	4	7	
Level of recipes production $h_{r,m}$	119	167	278	1000	
Amount of by-product used instead of raw materials $Y_{lmm'}$	B		C		D
	1000		556		179
Products to market Z_{mn}	α	β	γ	δ	ϵ
	500	500	500	500	500
By-products l unused at producers (production waste)	A	B	C		D
	0	0	0		0

Table 16 shows a total cost for the network of \$133K. All producers are represented in the network, but no producer uses all recipes available to them. Producer 1 uses recipe 2 at a production level of 119, and does not use recipe 1. Producer 2 uses recipe 3 at a production level of 278, recipe 4 at a production level of 167, and does not use recipe 5. Producer 3 uses recipe 7 at a production level of 1000, and does not use recipe 6. All demands were met exactly and all supply limits were satisfied. There was no by-product produced that were wasted (not used by any producer to as an input).

A simple sensitivity analysis can be conducted to understand the relationships between factors, such as cost components (distances and/or weights), supply limits, and demand thresholds. The marginal values indicate the behavior of the model for single incremental changes in values. The full output results and values can be found in the Supplemental Appendix for this scenario.

5.7 Problem 2

Problem Statement 2 – An industrial or eco-industrial network already exists. Develop a model to provide solutions that can be used for insight into the managed improvement of a facilitated eco-industrial network by adding or removing member firms.

Formulation

The second problem begins with the assumption that a network of firms already exists. The same basic model can be used as in problem 1, with modified data. The initial output results from the first problem will be used as the starting point for optimizing the network. Additional firms can be created, each with their own recipes, using the same types of input materials, to produce a product in demand by at least one of same five markets as the original network. The simplest approach to this problem is to use same methods used for minimization of cost for the problem 1, to test if the network expands to include the new firm. The output of the optimization will provide an indication if the new firm should be included in the network or not. The indication will be whether the recipes of the new firm have a production level greater than zero. It would only be considered as an addition to the network if at least one recipe has a nonzero production level $h_{r,m}$.

Problem 2: Eco-Industrial Network Evolution

Figure 31 - Conceptual Representation of Problem 2

In the figure above, two additional firms (4 and 5) have been made available to the network created by the problem 1 solution. The dashed arcs represent all possible material flows prior to knowledge of the producer recipes and technical coefficients. This knowledge is manufactured with coefficients that may challenge the problem 1 solution. The technological data for producer 4 and 5 is displayed in the table below.

Table 17 - Technical Coefficients for New Firm Recipes

Recipe r_m		Inputs	Outputs	
		$a_{r,l}$	$b_{r,n}$	$b_{r,l}$
8₄	→	4A+5B	2α	2D
9₄	→	4A+5B	α	0.5A+2B+D
10₅	→	A+C+D	3γ	
11₅	→	5C	0.5ε	0.5A

Producer 4 is likely to compete with producer 1 and recipe 1 directly, with two recipes 8 and 9. These recipes both have equal technical coefficients for inputs as recipe 1, but recipe 8 differs by producing greater relative quantities product outputs. Recipe 9 creates products less effectively by producing more by-products that could be utilized by other producers or end up as waste.

Producer 5 should compete with producer 2 and producer 3 using recipe 10 and 11. Recipe 10 produces product 3 from a less but more varied set of input coefficients. Recipe 11 produces the same product outputs as recipe 7, and produces only by-product A.

Producers 4 and 5 should not compete with each other.

Distances between nodes are representative of the distances portrayed in Figure 31. The additional data and GAMS program can be found in the Appendix.

Solution

The optimized solution for cost minimization for the eco-industrial network considering two additional available firms is illustrated in the figure below. The full GAMS output data can be found in the Supplemental Appendix.

Problem 2: Eco-Industrial Network Evolution

Figure 32 - Conceptual Representation of Problem 2 Solution

The table below shows that producer 5 has been added to the network, for a total cost to the network of \$126K, a reduction of approximately \$7K. Again, no raw material supplies are exhausted, all demands are met exactly, and no waste is produced in production, meaning all by-products were used as inputs in other producers. The total amount of by-products exchanged remained unchanged from the original network. This means that the addition of firm 5 had no effect on total material exchanged. Producer 5 has 100% clean production so creates no by-products, and so provides no inputs to the network. Additionally, producer 5 receives no by-products $Y_{lm'm}$ from any producers in the network. This means it only shares the same raw material suppliers as the network, so it can be questioned whether it should technically be considered a part of the network. Thus the definition of $h_{r,m} \geq 0$ as the only

criteria for acceptance to the network may be questioned in this scenario. Ultimately even though the total cost is lower, the inclusion of producer 5 only affects producer 2, by reducing its production level of recipe 3 from 167 to 45.

Table 18 - Summary of Significant Output Data for Problem 2

Total network cost f	\$126,019.84				
Raw (external) inputs used in recipes X_{lm}	A	B	C	D	
	1638	885	745	122	
Firms in the network m	1	2	3	5	
Recipes utilized r_m	2	3	4	7	10
Level of recipes production $h_{r,m}$	119	45	278	1000	122
Amount of by-product used instead of raw materials $Y_{lmm'}$	B		C	D	
	1000		556	179	
Products to market Z_{mn}	α	β	γ	δ	ϵ
	500	500	500	500	500
By-products / unused at producers (production waste)	A	B	C	D	
	0	0	0	0	

The model for this problem could be further extended to consider by-product exchange as a pre-requisite requirement for entrance to the network, as in many of the definitions in the literature. This may not be necessary though. The model could be extended to consider profit margins for each producer in the network for each product they produce. The model could also consider an “acceptable” profit, or more likely an acceptable production level $hlim_{r,m}$. In this case, a producer would declare their firm available to the network *only if* the threshold they set for production could be met.

5.8 Special Cases

The model proposed in this thesis is a simplified, macro level representation of a rudimentary eco-industrial network. However, we argue that the lack of detail and potential accuracy does not necessarily detract from the model's ability to provide a basic insight into material flow and cost implications for the decision making of the firms, network facilitators, and policymakers involved in planning, collaboration and management of the network. This model can be extended to reflect special cases that react to the four different stimuli for action (Environmental, Regulatory, Technological, and Demand) discussed in the methodology section of this thesis as illustrated in Figure 22.

SPECIAL CASE ONE: Environmental Impact

A new measure of environmental impact (*env*) can be included in the network. In reality, this would incorporate a wealth of information and data similar to that captured by tools such as LCA analyses. To demonstrate this model's flexibility, two simple environmental costs are created. The added costs are designed in this case to simulate government legislation. The first is a disposal fee for production by-products that are not used and resultantly become waste. The second could be interpreted as a "virgin material tax" to encourage exchange of by-products instead of raw materials. These are represented by the following notation and equations.

Environmental costing Notation:

<i>bpw_l</i>	Environmental cost for each by-product wasted
<i>vmt</i>	Virgin material scalar cost
<i>env</i>	Total environmental cost

Values:

$bpw_A = 10$ dollars per unit

$bpw_B = 11$ dollars per unit

$bpw_C = 12$ dollars per unit

$bpw_D = 13$ dollars per unit

$vmt = 200$ dollars per unit

Environmental cost function represented algebraically:

$$env = \sum_{l=1}^L \sum_{m=1}^M bpw_l * \left(\sum_{r_m=1}^{R_m} h_{r,m} b_{r,l} r_{m,r_m} - \sum_{m'=1}^M Y_{lmm'} \right) + \sum_{l=1}^L \sum_{m=1}^M vmt * X_{lm} \quad (17)$$

The entire network can be optimized to minimize environmental impact by changing the objective function by solving to minimize *ENV*. Alternatively, this cost can be added as a dollar value to the original objective function as in the equation below.

$$\text{Minimize } f = env + \sum_{l=1}^L \sum_{m=1}^M cx_{lm} X_{lm} + \sum_{m=1}^M \sum_{m'=1}^M cy_{lmm'} y_{lmm'} + \sum_{m=1}^M \sum_{n=1}^N cz_{mn} z_{mn} \quad (18)$$

An optimization example using the environmental costs can provide an insight into how a network might react to legislation. The GAMS input and results of this special case applied to the Problem 2 solution can be found in the Appendix.

The result in this case is not an increase in by-products exchange, but a huge increase in cost. Demands are met exactly. The indication is that the technological coefficients of the recipes do not create enough by-products to increase inputs. Any additional shipment to market would incur a huge cost in sourcing enough supply. The marginal values support this conclusion.

As a network facilitator the recommendation would be to explore changing technical coefficients.

SPECIAL CASE TWO: Eco-Efficient Innovation

This case has been shown to be the logical sequential step. Consider the case that an eco-industrial network has been established as in the previous case and problem 2, and producer choose to pursue individual opportunities to reduce cost by employing techniques such as Cleaner Production, Lean Six Sigma principles, or through Research and Development discover a more efficient method of production. This may alter the technological output coefficients for producers. This could result in a significant reduction of by-product outputs generated. In some networks, this may reduce waste but will also reduce the by-products available to other producers as inputs. The advancement in cleaner technology could also alter the technological input coefficients, meaning a producer can satisfy more demand for product outputs with less inputs required. This could again affect other producers because they could lose sinks for their by-product outputs.

In this case a sensitivity analysis could be performed where technological coefficients are systematically altered toward to increase eco-efficiency, to understand the effect on the overall network.

SPECIAL CASE THREE: Maximize Employment

It is also possible to expand the model to consider employment, incorporating an aspect of the Social portion of sustainability. A minimal input of information is again required to demonstrate this extension. Additional notation could be created and added to the model for employment created emp and jobs per unit of production of each recipe a producer uses $jobs_{h,r,m}$. The only information required in the simplest form of this case would be a scalar number from firms for the number of employees required per unit of production, for each recipe they can produce. It is then possible to calculate total network employment (emp).

Represented algebraically as

$$emp = \sum_{r_m=1}^{R_m} \sum_{m=1}^M jobs_{h_{r,m}} h_{r,m} r_{rm} \quad (19)$$

The network can be solved to maximize employment *emp* by changing the objective function to the equation above.

SPECIAL CASE FOUR: Optimize by Firm

Thus far the approach of this model has been to optimize from the perspective of “optimal” for the network as a whole. This is the equivalent of global optimization that does not necessarily account for the best interests of the individual firms. The model can be extended to consider the best interests of individual firms. In this case we would require notation and calculations for revenue *rev*. We are already aware of the costs involved external to the production of firms. The simplest method to calculate the revenues of firms would be to add a price for each product zp_n which would be multiplied by Z_{mn} . Represented algebraically as

$$rev = \sum_{m=1}^M \sum_{n=1}^N zp_n Z_{mn} \quad (20)$$

Many additional revenues and costs can be incorporated into the model, such as production costs for each firm, transaction costs and revenues for by-product or external material supply transactions.

Either the objective function could remain the same, minimizing the total cost for the network, or it could be changed to optimize for an individual firm, incorporating the cost functions such as *rev*.

SPECIAL CASE FIVE: Optimize for Product

An optimization by one or more product types or by input type can be achieved through this model in several ways. Products can be set to have a huge cost, or a huge profit associated with them to achieve a product-based goal instead of algebraic constraints. Alternatively, a product or a particular type of by-product could be considered purely as a waste with a great environmental impact. For example, a product could be found to be extremely harmful to the environment, and be unrecyclable. The model could be extended to incorporate this. Demand for the product could be reduced to zero. The demand threshold constraint becomes $D_n \geq 0$. Thus any production of this material n will be a cost, and the network would optimize to avoid this production. Demand constraints and product output weights have so far remained unchanged, but could be manipulated by the network facilitator or by government policy to affect the distribution of production for each product. The objective function could simply be changed to maximize or minimize the production of any one or group of products.

SPECIAL CASE SIX: Network Spanning Multiple Regulatory Regions

There are multiple opportunities for regulatory or incentive based legislation to impact the optimal eco-industrial network concluded by any of the models proposed so far. The sensitivity analysis provides an indication as to how the model reacts to variations in the input data. A government could provide tax relief for firms operating within an eco-industrial network to incentivize firms' willingness to cooperate and provide information that makes them available to eco-industrial network planners or facilitators. For example, a 50% tax break

on transportation within the network could be represented simply by changing the transportation cost function for by-products to

$$\sum_{m=1}^M \sum_{m'=1}^M (cy_{lmm'}y_{lmm'})/2 \quad (21)$$

Governments also have the ability to increase costs (taxes) for waste, as in Special Case 1, or transportation or any of the other cost factors.

However, as the scope of eco-industrial networks or circular economies increase the situation arises where a network considers membership of many firms over a broad region, spanning multiple regulatory or legislative regions. We can demonstrate these considerations with another extension of the model by drawing boundaries around nodes in different regions and altering the cost of arcs (transportation in the basic case) between nodes. This is represented conceptually in Figure 33 where two regulatory regions are considered.

The shaded background areas represent boundaries in the figure. A government tariff is an example of a scenario where increase costs would occur for all materials traveling across this boundary. The case could become as complicated as necessary, with facility overhead taxes and costs varying across regions.

Figure 33- Conceptual Representation of a Network Spanning Two Regulatory Regions

(Orange Arcs Represent Cross-Boundary Shipping Paths)

SPECIAL CASE SEVEN: Reverse Flows

One argument made throughout this thesis is that it is necessary to incorporate reverse material flows, or return flows from the final customer/consumer, back into the production cycle after the useful life of a product. For simplicity and for emphasis on industrial symbiosis, the configurations of the models proposed have incorporated only forward flows, without consideration of product flows at the end of their useful life. However, the models can easily be extended to include reverse flows in network decision making. Remanufacturers or recyclers can be introduced into the network. There are several methods to incorporate reverse flows. One of the simplest is considered in this case. Conceptual representations of this special case can be seen in Figure 34 and Figure 35.

To exemplify this flexibility a single recycler is considered, and is added to the set of producers as Producer 4. The recycler can has the capability of recycling products 3 and 5. The recycler has particular technological coefficients (recipes) for transforming products back into usable inputs from each unit of end-of-life (EOL) products 3 and 5.

Figure 34 – Material Flows for Recycler

EIN - Special Case 7 - Reverse Flows

Figure 35 - Conceptual Representation of a Network Inclusive of Reverse Flows

In the figure above the blue lines represent the flows of collected End-of-Life products from markets to the recycler. The darkest green lines show the possible by-product flows of inputs from the recycler to other producers.

An example technological coefficients matrix for the recycler is shown below. The recycler has two recipes, 13 and 14. Each recipe shows the by-product outputs recovered from one unit of collected end-of-life product.

Table 19 - Recycler technological coefficients

Recipe r_m		Inputs (EOL Products)	Outputs (By-product Inputs)
			$b_{r,t}$
12₄	→	γ	$0.5A + 2D$
13₄	→	ϵ	$0.25A + 0.25B$

In reality, there would likely be a factor of entropy, which reduces the quality and or volume of usable material recovered, and there may be ‘waste’ material whose quality that has been downgraded to a level that cannot be recycled. In lieu of explicit calculations, this is considered by very low levels of by-product outputs in Table 19.

In consideration of supply limits in this case, only 25% of the products are recovered from the respective markets at end-of-life. Supply capacity available to the recycler would be 25% of product outputs from markets 3 and 5. The supply volumes for the recycler can be represented algebraically as:

$$\text{Supply of EOL Product 3} \quad S_5 = 0.25 * \sum_{M=1}^{M=5} Z_{m3} \quad (22)$$

$$\text{Supply of EOL Product 5} \quad S_6 = 0.25 * \sum_{M=1}^{M=5} Z_{m5} \quad (23)$$

A simple method to constrain the supply of EOL product use is to limit the rate of recipes ($h_{r,m}$) at the recycler ($h_{12,4}$ and $h_{13,4}$). This constraint is shown below:

$$\text{Limit EOL Product 3 Use} \quad 0.25 * \sum_{M=1}^{M=5} Z_{m3} \geq h_{12,4} \quad (24)$$

$$\text{Limit EOL Product 5 Use} \quad 0.25 * \sum_{M=1}^{M=5} Z_{m5} \geq h_{13,4} \quad (25)$$

An additional variable could be used instead of 0.25, to allow flexibility in changing EOL product recovery rates. Also, a legislation requiring the use of all recycled material could be modeled by changing the ‘greater than equal’ ($\geq$) rule to ‘equal’ instead ($=$).

The objective function can remain the same if appropriate costs, weights, and distances are introduced for the recycler and the flows to and from it. So with simple extensions to the model the reverse flows and recovery of end-of-life materials can be considered. This extension can show the effects at both ends of the production cycle. Firstly the positive effect of diverting waste away from waste sinks and back into the production and use cycles and as a result, the secondary effect of reducing the need for raw material resource extraction and use.

CHAPTER 6 – CONCLUSION

6.1 SUMMARY

This thesis cast the ambitious task of building a design paradigm and approach towards sustainable development. An extensive review of the literature was conducted across a multitude of related and unrelated research fields within and out with the traditional scope of sustainability. The collaborative, systems oriented and scientifically grounded nature of industrial ecology and sustainable development fits well with many principles of industrial and systems engineering and operations research.

A considerable literature review of industrial ecology has provided a robust background of concepts and the current state-of-the-art in eco-industrial development. The progression through cases of increasing scale and complexity affords an intuition into the objectives and progress of researchers in the field, and the challenges facing practitioners in reality. The complexity and scale of challenges illustrates the necessity for collaborative, multi-disciplinary and inter-disciplinary approaches to solutions, as prescribed by the the 2014 WEF Annual Meeting, and the 2012 Rio+20 Sustainability Summit reports.

The many challenges of practical industrial ecology applications were revealed in the literature review. Extensions to the field are both discovered in existing industrial ecology literature, and intuitively linked through their absence from the literature. The additional linkages made between industrial ecology and previously poorly linked fields such as supply chain and logistics, and reverse logistics, confirms that a broadening of industrial ecology scope is necessary in order to fully address the challenges and opportunities in sustainable development. Significant existing linkages discovered in the literature review were extended.

These fields include multiple engineering disciplines, natural sciences, recycling, waste management and several social sciences.

The literature review shows a progression from an expansive initial boundary to a narrow selection of features from various fields. Selected features were absorbed into the ideas of industrial ecology in this thesis to convey a set of paradigms and principles that aid conceptual understanding and practical solutions to two specific product supply network problems.

The model developed to address the first problem of planning an eco-industrial network from a set of existing firms, has been shown to offer significant insight into the decision making process for such a problem. The model finds an optimal solution based on economic and technical factors. The additional special cases of the problem can effectively consider social factors such as employment; environmental factors such as pollution or waste minimization; policy factors such as tariffs or variations in tax legislation; and reverse flows and end-of-life recovery. The second problem provides an acceptable level of perspective for the management and evolution of an eco-industrial network already in existence.

The models both provide sensitivity results offering insight into the behavior of an eco-industrial network based on various economic, environmental and social criteria. Both models are shown to demonstrate flexibility that extends to a range of further relevant and more complex problems. Variations of these models can be scaled up to consider 'big data', to include massive arrays of producers, suppliers, demand markets and regulations. In this thesis very small cases were considered to provide an understanding of the powerful insights that simple models may provide.

The models in this thesis are explored from the perspective of a centralized decision maker or facilitator. In the Chinese example of Circular Economy, the central government are

able to exercise considerable independent authority in decision making. The same is often not true of democratic societies and capitalist economies. Many industrial leaders, firms, shareholders and other organizations and stakeholders would be reluctant to concede autonomous decision making power to an external body to act in the interest of the 'greater good'. The example framework in the literature review, set by NISP and Synergy International, is effective in establishing leadership groups and facilitating synergistic decisions between firms. A combination of more sophisticated modeling approaches and an NISP type framework for collaboration is proposed as an ideal.

6.2 FUTURE RESEARCH

6.2.1 Future Research Collaboration

This thesis has pointed to several fields that require unification for progress in future research. The most notable three areas are economics, behavioral sciences, supply chain, and industrial ecology/engineering. A better collective understanding of the principles underlying each can significantly speed both progress of research, and the gain of critical mass required for the concepts of circular economy and industrial ecosystems to become the norm of global commerce and society.

6.2.2 Future Models

Future models require detailing of the model with parameters from areas of social and behavioral sciences, and also more sophisticated quantitative methods of operations research that can incorporate the reverse logistics, waste recovery, recycling and refurbishment, among other factors. The models in this thesis significantly abbreviate real-world problems. The models may omit many of the social and external challenges arising in practical cases of sustainable development planning.

Many additional issues were highlighted in the literature review as largely social issues, such a trust, and idiosyncratic management behavior. Future models should consider some of the assumptions related to collaboration and feasibility, made in this thesis in order to generate the abbreviated problems this thesis' models were designed to solve.

6.2.3 Does Industrial Ecology Fall Short of Sustainability?

Throughout this research into sustainability and the subsequent progression into the field of industrial ecology research, the complexity of the challenges in realizing a cultural socio-economic shift towards embedding industrial ecology as a business-as-usual norm grew. The unsustainable nature of business depicted by most of the implemented cases of industrial symbiosis became increasingly apparent. These cases showed a trend indicative of the required systemic transformation. This need for additional change in paradigm was articulated by Peter Wells and Clovis Zapata recently in the Journal of Industrial Ecology (Wells & Zapata, 2012). In their article titled “Renewable Eco-Industrial Development: A New Frontier for Industrial Ecology?” Wells and Zapata challenge the current scope of industrial ecology, and call for an embrace of a “more proactive, interventionist stance” towards meeting worldwide sustainability obstacles. The idealistic article provokes the traditional concept of industrial ecology and addresses one gap towards meeting sustainability. The authors note that many cases of industrial symbiosis are reliant on non-renewable resources, including the poster child case study of Kalundborg:

“eco-industrialism does not appear to require that the products of this complex are themselves sustainable, or that the raw materials used are renewable, even if the approach does actively highlight the reduction of virgin raw material as an important benefit.” (Wells & Zapata, 2012)

The authors advocate for industrial ecology to aspire towards renewable “eco-industrialism”. Several examples are offered based around biorefineries, where renewable resources are inputs for industrial ecosystems, including sugarcane ethanol based bioplastics industry in Brazil, which has been used in cosmetics, packaging, toys and for fueling automobiles. However, it is also emphasized that the prospect of biomass renewables as a substitute for conventional non-renewable resources (fossil fuels in particular), raise a plethora

of economic, social and environmental issues that would have to be solved. They conclude that three significant features exist in the paradigm of renewable eco-industrialism. Firstly, industrial ecology will be required to progress deeper into the realm of system design, over retrofitting or replicating current industrial systems, in order to fit “existing biomass availability in the most efficient manner possible”. Secondly, the young field of industrial ecology will have to navigate a tricky balance in order to remain considered as a legitimate science, grounded in solid methodology and rooted in robust historical data for analysis, and entering the role of design under the new model. The third feature is that a rapid, global sociotechnical shift is necessary to achieve “some form” of sustainability, and that renewable eco-industrialism is “probably” a part of it.

Can industrial ecology grow to become a part of the long-term solution in this progressive shift to a higher level of systemic sustainability, instead of a tinkering optimizer of the current system? If the answer is to be yes, then a more multidisciplinary approach to planning and design is required, and market forces will have to shift to make sustainable industrial ecosystems economically viable, and desirable.

GLOSSARY

ECO-EFFICIENCY:

Management - A World Business Council for Sustainable Development publication claims to have coined the term eco-efficiency in 1991. The WBCSD use a simple slogan for eco-efficiency, “creating more value with less impact” (WBCSD, 2000). They define the terms as “*a management philosophy which encourages business to search for environmental improvements that yield parallel economic benefits.*”

Logistics - Eco-efficiency has also been defined in Logistics Management in different terms, which assess a quantifiable *trade-off* between environmental and economic factors, defined as “*the set of solutions in which it is not possible to decrease environmental damage, or increase total environmental quality of each environmental category, unless increasing costs.*” (Neto, Walther, Bloemhof, van Nunen, & Spengler, 2009).

INDUSTRIAL ECOSYSTEM: A community or network of companies and other organizations in a region who choose to interact by exchanging, selling, using, and reusing by-products and/or energy in a way that provides one or more of the following eco-efficiency benefits over traditional, non-linked operations (Lowe, 1997):

1. Reduction in the use of virgin materials as resource inputs
2. Increased energy efficiency leading to reduced systemic energy use
3. Reduction in the volume of waste products requiring disposal (with the added benefit of preventing disposal-related pollution).
4. Increase in the amount and types of process outputs that have market value.

CLEANER PRODUCTION (CP): “*the continuous application of an integrated preventive environmental strategy applied to processes, products, and services to increase eco-efficiency and reduce risks to humans and the environment.*” (United Nations Environment Programme)

CARBON FOOTPRINT: *"The carbon footprint is a measure of the exclusive total amount of carbon dioxide emissions that is directly and indirectly caused by an activity or is accumulated over the life stages of a product."* (Wiedmann & Minx, 2008)

INDUSTRIAL ECOLOGY: A holistic, interdisciplinary systemic approach to optimizing human commercial activity, principally through flows of substances and energy, through effective design inspired by nature's ecological processes, where success is defined by continuous economic, environmental, and social enhancement.

ECONOMIC SOCIOLOGY: Most simply defined as *"the sociological perspective applied to economic phenomena"* and *"the application of the frames of reference, variables, and explanatory models of sociology so that complex of activities concerned with the production, distribution, exchange, and consumption of scarce goods and services."* (Smelser & Swedberg, 2010)

ECOLOGY: Simply defined by Merriam Webster as *"a branch of science concerned with the inter-relationships of organisms and their environments"*

INDUSTRIAL SYMBIOSIS (IS): In the context of this thesis, IS can be defined as cooperative exchange of materials, energy, water, or utilities between firms, that are not the primary product of either firm

ECO-INDUSTRIAL PARK (EIP): A summary definition of EIPs is a community of commercial actors or firms connected by energy and material by-product flows, possibly also sharing additional resources, co-located in a bounded geographic area,.

ECO-INDUSTRIAL NETWORK (EIN): These networks can be understood as a dynamic version of eco-industrial parks, not bounded by geography. Eco-industrial networks are

dynamic in the sense that their scale, number of connections, type of connections and members can change frequently. In the context of this thesis eco-industrial networks are market driven, and so their makeup is responds to market forces, including environmental and societal influences.

BIOSPHERE: Simply in the context of this thesis, the Biosphere includes all naturally occurring elements and ecosystems and their interactions, specifically excluding man-made materials and systems. Biosphere is defined by Merriam Webster as “*Relatively thin life-supporting stratum of the earth's surface, extending from a few miles into the atmosphere to the deep-sea vents of the oceans. The biosphere is a global ecosystem that can be broken down into regional or local ecosystems, or biomes. Organisms in the biosphere are classified into trophic levels and communities.*”

BIOMIMICRY: The study of nature’s processes, species, systems, holons (system of systems), and materials, with a view to replicating nature’s design, or using it as inspiration for solving human problems.

TECHNOSPHERE: This term is meant in this thesis as McDonough and Braungart used it in Cradle-to-Cradle where the technosphere comprises all materials useful as “*technical nutrients...useful for...the systems of industrial processes*” (McDonough & Braungart, Cradle to Cradle, 2002).

METABOLISM: Metabolism can be defined as the total materials and flows required for a system to function. It has also been specifically defined to include these processes (Beck, Liem, & Simpson, 1991):

- All the chemical processes by which food and its derivatives are broken down to yield new building blocks and energy. This segment of metabolism is termed catabolism.

- All the chemical processes by which living cells and tissues are produced and built up. This is anabolism (buildup of new molecules by biosynthesis).
- All the regulatory mechanisms that govern these intricate systems.”

INDUSTRIAL METABOLISM: An extension to the biological concept of metabolism, as applied to industry “*the whole integrated collection of physical processes that convert raw materials and energy, plus labour, into finished products and wastes..*” (Ayres R. , 1994).

SOCIO-ECONOMIC METABOLISM: Similar to Industrial Metabolism, but the definition extends to include all material/energy flows for society as a whole. Boundaries are difficult to draw, but are typically referenced as national boundaries, or subsystems such as cities, or industries. Measurement is closely tied to Material Flow Analysis. (Fischer-Kowalski & Hüttler, 1999)

MATERIAL FLOW ANALYSIS (MFA): Typically very detailed level of analysis of material transfers within a defined system boundary. Can be as detailed as the atomic level within chemical transformations, or as high a level as product flows within entire industries. MFA is not mutually exclusive as a technique from LCA or Input-Output approaches, and is often incorporated within different techniques and software (Bailey, Allen, & Bras, 2004).

LIFE CYCLE ANALYSIS (LCA): “*A tool for identifying and evaluating the environmental impact aspects of products and services from the “cradle to the grave”: from the extraction of resource inputs to the eventual disposal of the product or its waste.*” (International Organization for Standardization Central Secretariat, 2009).

INPUT-OUTPUT ANALYSIS (I-O Analysis): This is a powerful method of analysis for large scale networks. Input-output economics was first developed by Wassily Leontief to

quantitatively link the flows and interdependencies of the inputs and outputs of each individual sector of the US economy to each other and to final demand, all in economic dollar values (Leontief, 1936). Input-Output analyses can capture enormous systems and their interactions, but have been criticized for their aggregate nature. It can also be a challenging tool for use in network planning. It is more easily adapted for interdependencies of an already existing system, unless precise metrics are available for an easily predictable future network state.

Input-Output analyses have also been extended to include environmental aspects. Such branches include Environmental Input-Output Analysis and Input-Output LCA approaches. These analyses are explored fully Hendrickson et.al, and include hybrid approaches and disaggregation of data (Hendrickson, Lave, & Matthews). These are data intensive techniques.

NETWORK ORCHESTRATION THEORY: Facilitation of social encounters to foster mutually beneficial connections. The collection of connections forms a network.

RESILIENCY: The Merriam Webster dictionary definition provides a definition consistent with the context in this thesis: *“the ability to become strong, healthy, or successful again after something bad happens”*

APPENDICES

Appendix A: FULL MODEL ALGEBRA – Basic Model

External Supply Constraints

Sets used in constraint:

$L\{A...D\}$ Set of 4 Supply Nodes

$M\{1...3\}$ Set of 3 Producer Nodes

Symbols:

S_l The supply of input l

X_{lm} Amount of flow of l From External Supply Node l to Producer Node m

Sum total of inputs X_{lm} supplied to set of producers M from supply node l cannot exceed total quantity available at supply node S_l :

$$\boxed{\sum_{m=1}^M X_{lm} \leq S_l \quad \forall l}$$

Sum supply of A to set of producers M must not exceed supply S_A :

$$\sum_{m=1}^3 X_{Am} \leq S_A$$

Sum supply of B to set of producers M must not exceed supply S_B :

$$\sum_{m=1}^3 X_{Bm} \leq S_B$$

Sum supply of C to set of producers M must not exceed supply S_C :

$$\sum_{m=1}^3 X_{Cm} \leq S_C$$

Sum supply of D to set of producers M must not exceed supply S_D :

$$\sum_{m=1}^3 X_{Dm} \leq S_D$$

Final Equations:

$$X_{A1} + X_{A2} + X_{A3} \leq S_A$$

$$X_{B1} + X_{B2} + X_{B3} \leq S_B$$

$$X_{C1} + X_{C2} + X_{C3} \leq S_C$$

$$X_{D1} + X_{D2} + X_{D3} \leq S_D$$

Set of External Market Demand Constraints

Sets:

Set of 5 Demand Nodes $N\{1...5\}$

Set of 3 Producer Nodes $M = \{1...3\}$

Symbols:

D_n Demand for output n

Z_{mn} Amount of Output flow from Producer Node m to External Demand Node n

Sum total of outputs Z_{mn} received by external market node n from set of producers M must equal or exceed demand D_n at external market node n :

$$\sum_{m=1}^M Z_{mn} \geq D_n \quad \forall n$$

Sum total of outputs received by external market node 1 from set of producers M must equal or exceed demand at external market node 1:

$$\sum_{m=1}^3 Z_{m1} \geq D_1$$

Sum total of outputs received by external market node 2 from set of producers M must equal or exceed demand at external market node 2:

$$\sum_{m=1}^3 Z_{m2} \geq D_2$$

Sum total of outputs received by external market node 3 from set of producers M must equal or exceed demand at external market node 3:

$$\sum_{m=1}^3 Z_{m3} \geq D_3$$

Sum total of outputs received by external market node 4 from set of producers M must equal or exceed demand at external market node 4:

$$\sum_{m=1}^3 Z_{m4} \geq D_4$$

Sum total of outputs received by external market node 5 from set of producers M must equal or exceed demand at external market node 5:

$$\sum_{m=1}^3 Z_{m5} \geq D_5$$

Final Equations:

$$Z_{11} + Z_{21} + Z_{31} \geq D_1$$

$$Z_{12} + Z_{22} + Z_{32} \geq D_2$$

$$Z_{13} + Z_{23} + Z_{33} \geq D_3$$

$$Z_{14} + Z_{24} + Z_{34} \geq D_4$$

$$Z_{15} + Z_{25} + Z_{35} \geq D_5$$

Three Material Transformation Constraints for Producer Nodes

Sets:

Set of recipes R , $\{1 \dots 7\}$

Set of producers M , $\{1 \dots 3\}$

Set of inputs L , $\{A \dots D\}$

Set of markets N , $\{1 \dots 5\}$

Symbols:

r_m Recipe r at producer m

$h_{r,m}$ Level of production h of recipe r at producer m

$a_{r,l}$ Inputs required in Recipe r of type l

$b_{r,n}$ Product outputs produced using recipe r_m of type n

$b_{r,l}$ By-product outputs produced using recipe r_m of type l

$rm_{r,m}$ Binary array of corresponding recipes r available in producers m

Z_{mn} Amount of Output flow from Producer Node m to External Demand Node n

$a_{rl} = b_{r,n} + b_{r,l}$ Technical coefficients for each recipe r_m , inputs l are transformed by into products n and by-products l which can be used as inputs l by other producers m' .

This flow is represented conceptually in figure 22

Use of All Inputs in Recipes Constraint

For all inputs and producers, all inputs received by a producer must be used in recipes in that producer.

Represented algebraically as:

$$X_{lm} + \sum_{m'=1}^M Y_{lm'm} = \sum_{r=1}^R h_{r,m} a_{r,l} rm_{r,m} \quad \forall l, m$$

Final Equations:

$$\begin{aligned} X_{A1} + Y_{A21} + Y_{A31} \\ = h_1 a_{1A} RM_{1,1} + h_2 a_{2,A} RM_{2,1} + h_3 a_{3A} RM_{3,1} + h_4 a_{4A} RM_{4,1} + h_5 a_{5A} RM_{5,1} \\ + h_6 a_{6A} RM_{6,1} + h_7 a_{7A} RM_{7,1} \end{aligned}$$

$$\begin{aligned}
X_{A2} + Y_{A12} + Y_{A32} \\
&= h_1 a_{1A} RM_{1,2} + h_2 a_{2A} RM_{2,2} + h_3 a_{3A} RM_{3,2} + h_4 a_{4A} RM_{4,2} + h_5 a_{5A} RM_{5,2} \\
&+ h_6 a_{6A} RM_{6,2} + h_7 a_{7A} RM_{7,2}
\end{aligned}$$

$$\begin{aligned}
X_{A3} + Y_{A13} + Y_{A23} \\
&= h_1 a_{1A} RM_{1,3} + h_2 a_{2A} RM_{2,3} + h_3 a_{3A} RM_{3,3} + h_4 a_{4A} RM_{4,3} + h_5 a_{5A} RM_{5,3} \\
&+ h_6 a_{6A} RM_{6,3} + h_7 a_{7A} RM_{7,3}
\end{aligned}$$

$$\begin{aligned}
X_{B1} + Y_{B21} + Y_{B31} \\
&= h_1 a_{1B} RM_{1,1} + h_2 a_{2B} RM_{2,1} + h_3 a_{3B} RM_{3,1} + h_4 a_{4B} RM_{4,1} + h_5 a_{5B} RM_{5,1} \\
&+ h_6 a_{6B} RM_{6,1} + h_7 a_{7B} RM_{7,1}
\end{aligned}$$

$$\begin{aligned}
X_{B2} + Y_{B12} + Y_{B32} \\
&= h_1 a_{1B} RM_{1,2} + h_2 a_{2B} RM_{2,2} + h_3 a_{3B} RM_{3,2} + h_4 a_{4B} RM_{4,2} + h_5 a_{5B} RM_{5,2} \\
&+ h_6 a_{6B} RM_{6,2} + h_7 a_{7B} RM_{7,2}
\end{aligned}$$

$$\begin{aligned}
X_{B3} + Y_{B13} + Y_{B23} \\
&= h_1 a_{1B} RM_{1,3} + h_2 a_{2B} RM_{2,3} + h_3 a_{3B} RM_{3,3} + h_4 a_{4B} RM_{4,3} + h_5 a_{5B} RM_{5,3} \\
&+ h_6 a_{6B} RM_{6,3} + h_7 a_{7B} RM_{7,3}
\end{aligned}$$

$$\begin{aligned}
X_{C1} + Y_{C21} + Y_{C31} \\
&= h_1 a_{1C} RM_{1,1} + h_2 a_{2C} RM_{2,1} + h_3 a_{3C} RM_{3,1} + h_4 a_{4C} RM_{4,1} + h_5 a_{5C} RM_{5,1} \\
&+ h_6 a_{6C} RM_{6,1} + h_7 a_{7C} RM_{7,1}
\end{aligned}$$

$$\begin{aligned}
& X_{C2} + Y_{C12} + Y_{C32} \\
&= h_1 a_{1C} RM_{1,2} + h_2 a_{2C} RM_{2,2} + h_3 a_{3C} RM_{3,2} + h_4 a_{4C} RM_{4,2} + h_5 a_{5C} RM_{5,2} \\
&+ h_6 a_{6C} RM_{6,2} + h_7 a_{7C} RM_{7,2}
\end{aligned}$$

$$\begin{aligned}
& X_{C3} + Y_{C13} + Y_{C23} \\
&= h_1 a_{1C} RM_{1,3} + h_2 a_{2C} RM_{2,3} + h_3 a_{3C} RM_{3,3} + h_4 a_{4C} RM_{4,3} + h_5 a_{5C} RM_{5,3} \\
&+ h_6 a_{6C} RM_{6,3} + h_7 a_{7C} RM_{7,3}
\end{aligned}$$

Flow of All Product Outputs to Market Constraint

For all producers and markets, the product outputs produced must flow to markets.

Represented algebraically as:

$$\sum_{r=1}^R h_{r,m} b_{r,n} rm_{r,m} = Z_{mn} \quad \forall m, n$$

Final Equations:

Producer 1 Equations

$$h_1 b_{1,1} RM_{1,1} + h_2 b_{2,1} RM_{2,1} + h_3 b_{3,1} RM_{3,1} + h_4 b_{4,1} RM_{4,1} + h_5 b_{5,1} RM_{5,1} + h_6 b_{6,1} RM_{6,1} + h_7 b_{7,1} RM_{7,1} = Z_{11}$$

$$h_1 b_{1,2} RM_{1,1} + h_2 b_{2,2} RM_{2,1} + h_3 b_{3,2} RM_{3,1} + h_4 b_{4,2} RM_{4,1} + h_5 b_{5,2} RM_{5,1} + h_6 b_{6,2} RM_{6,1} + h_7 b_{7,2} RM_{7,1} = Z_{12}$$

$$h_1 b_{1,3} RM_{1,1} + h_2 b_{2,3} RM_{2,1} + h_3 b_{3,3} RM_{3,1} + h_4 b_{4,3} RM_{4,1} + h_5 b_{5,3} RM_{5,1} + h_6 b_{6,3} RM_{6,1} + h_7 b_{7,3} RM_{7,1} = Z_{13}$$

$$h_1 b_{1,4} RM_{1,1} + h_2 b_{2,4} RM_{2,1} + h_3 b_{3,4} RM_{3,1} + h_4 b_{4,4} RM_{4,1} + h_5 b_{5,4} RM_{5,1} + h_6 b_{6,4} RM_{6,1} + h_7 b_{7,4} RM_{7,1} = Z_{14}$$

$$h_1 b_{1,5} RM_{1,1} + h_2 b_{2,5} RM_{2,1} + h_3 b_{3,5} RM_{3,1} + h_4 b_{4,5} RM_{4,1} + h_5 b_{5,5} RM_{5,1} + h_6 b_{6,5} RM_{6,1} + h_7 b_{7,5} RM_{7,1} = Z_{15}$$

Producer 2 Equations

$$h_1 b_{1,1} RM_{1,2} + h_2 b_{2,1} RM_{2,2} + h_3 b_{3,1} RM_{3,2} + h_4 b_{4,1} RM_{4,2} + h_5 b_{5,1} RM_{5,2} + h_6 b_{6,1} RM_{6,2} + h_7 b_{7,1} RM_{7,2} = Z_{21}$$

$$h_1 b_{1,2} RM_{1,2} + h_2 b_{2,2} RM_{2,2} + h_3 b_{3,2} RM_{3,2} + h_4 b_{4,2} RM_{4,2} + h_5 b_{5,2} RM_{5,2} + h_6 b_{6,2} RM_{6,2} + h_7 b_{7,2} RM_{7,2} = Z_{22}$$

$$h_1b_{1,3}RM_{1,2} + h_2b_{2,3}RM_{2,2} + h_3b_{3,3}RM_{3,2} + h_4b_{4,3}RM_{4,2} + h_5b_{5,3}RM_{5,2} + h_6b_{6,3}RM_{6,2} \\ + h_7b_{7,3}RM_{7,2} = Z_{23}$$

$$h_1b_{1,4}RM_{1,2} + h_2b_{2,4}RM_{2,2} + h_3b_{3,4}RM_{3,2} + h_4b_{4,4}RM_{4,2} + h_5b_{5,4}RM_{5,2} + h_6b_{6,4}RM_{6,2} \\ + h_7b_{7,4}RM_{7,2} = Z_{24}$$

$$h_1b_{1,5}RM_{1,2} + h_2b_{2,5}RM_{2,2} + h_3b_{3,5}RM_{3,2} + h_4b_{4,5}RM_{4,2} + h_5b_{5,5}RM_{5,2} + h_6b_{6,5}RM_{6,2} \\ + h_7b_{7,5}RM_{7,2} = Z_{25}$$

Producer 3 Equations

$$h_1b_{1,1}RM_{1,3} + h_2b_{2,1}RM_{2,3} + h_3b_{3,1}RM_{3,3} + h_4b_{4,1}RM_{4,3} + h_5b_{5,1}RM_{5,3} + h_6b_{6,1}RM_{6,3} \\ + h_7b_{7,1}RM_{7,3} = Z_{31}$$

$$h_1b_{1,2}RM_{1,3} + h_2b_{2,2}RM_{2,3} + h_3b_{3,2}RM_{3,3} + h_4b_{4,2}RM_{4,3} + h_5b_{5,2}RM_{5,3} + h_6b_{6,2}RM_{6,3} \\ + h_7b_{7,2}RM_{7,3} = Z_{32}$$

$$h_1b_{1,3}RM_{1,3} + h_2b_{2,3}RM_{2,3} + h_3b_{3,3}RM_{3,3} + h_4b_{4,3}RM_{4,3} + h_5b_{5,3}RM_{5,3} + h_6b_{6,3}RM_{6,3} \\ + h_7b_{7,3}RM_{7,3} = Z_{33}$$

$$h_1b_{1,4}RM_{1,3} + h_2b_{2,4}RM_{2,3} + h_3b_{3,4}RM_{3,3} + h_4b_{4,4}RM_{4,3} + h_5b_{5,4}RM_{5,3} + h_6b_{6,4}RM_{6,3} \\ + h_7b_{7,4}RM_{7,3} = Z_{34}$$

$$h_1b_{1,5}RM_{1,3} + h_2b_{2,5}RM_{2,3} + h_3b_{3,5}RM_{3,3} + h_4b_{4,5}RM_{4,3} + h_5b_{5,5}RM_{5,3} + h_6b_{6,5}RM_{6,3} \\ + h_7b_{7,5}RM_{7,3} = Z_{35}$$

No By-product Wasted Constraint

For all inputs and producers, all by-products produced must be used as inputs in recipes, resulting in zero waste remaining at producers.

This constraint is expressed algebraically by the equation below

$$\sum_{r=1}^R h_{r,m} b_{r,l} r m_{r,m} \geq \sum_{m'=1}^M Y_{lmm'} \quad \forall l, m$$

Final Equations:

Producer 1 Equations:

$$h_1 b_{1,A} RM_{1,1} + h_2 b_{2,A} RM_{2,1} + h_3 b_{3,A} RM_{3,1} + h_4 b_{4,A} RM_{4,1} + h_5 b_{5,A} RM_{5,1} + h_6 b_{6,A} RM_{6,1} + h_7 b_{7,A} RM_{7,1} \geq Y_{A11} + Y_{A12} + Y_{A13}$$

$$h_1 b_{1,B} RM_{1,1} + h_2 b_{2,B} RM_{2,1} + h_3 b_{3,B} RM_{3,1} + h_4 b_{4,B} RM_{4,1} + h_5 b_{5,B} RM_{5,1} + h_6 b_{6,B} RM_{6,1} + h_7 b_{7,B} RM_{7,1} \geq Y_{B11} + Y_{B12} + Y_{B13}$$

$$h_1 b_{1,C} RM_{1,1} + h_2 b_{2,C} RM_{2,1} + h_3 b_{3,C} RM_{3,1} + h_4 b_{4,C} RM_{4,1} + h_5 b_{5,C} RM_{5,1} + h_6 b_{6,C} RM_{6,1} + h_7 b_{7,C} RM_{7,1} \geq Y_{C11} + Y_{C12} + Y_{C13}$$

$$h_1 b_{1,D} RM_{1,1} + h_2 b_{2,D} RM_{2,1} + h_3 b_{3,D} RM_{3,1} + h_4 b_{4,D} RM_{4,1} + h_5 b_{5,D} RM_{5,1} + h_6 b_{6,D} RM_{6,1} + h_7 b_{7,D} RM_{7,1} \geq Y_{D11} + Y_{D12} + Y_{D13}$$

Producer 2 Equations:

$$h_1b_{1,A}RM_{1,2} + h_2b_{2,A}RM_{2,2} + h_3b_{3,A}RM_{3,2} + h_4b_{4,A}RM_{4,2} + h_5b_{5,A}RM_{5,2} + h_6b_{6,A}RM_{6,2} + h_7b_{7,A}RM_{7,2} \geq Y_{A21} + Y_{A22} + Y_{A23}$$

$$h_1b_{1,B}RM_{1,2} + h_2b_{2,B}RM_{2,2} + h_3b_{3,B}RM_{3,2} + h_4b_{4,B}RM_{4,2} + h_5b_{5,B}RM_{5,2} + h_6b_{6,B}RM_{6,2} + h_7b_{7,B}RM_{7,2} \geq Y_{B21} + Y_{B22} + Y_{B23}$$

$$h_1b_{1,C}RM_{1,2} + h_2b_{2,C}RM_{2,2} + h_3b_{3,C}RM_{3,2} + h_4b_{4,C}RM_{4,2} + h_5b_{5,C}RM_{5,2} + h_6b_{6,C}RM_{6,2} + h_7b_{7,C}RM_{7,2} \geq Y_{C21} + Y_{C22} + Y_{C23}$$

$$h_1b_{1,D}RM_{1,2} + h_2b_{2,D}RM_{2,2} + h_3b_{3,D}RM_{3,2} + h_4b_{4,D}RM_{4,2} + h_5b_{5,D}RM_{5,2} + h_6b_{6,D}RM_{6,2} + h_7b_{7,D}RM_{7,2} \geq Y_{D21} + Y_{D22} + Y_{D23}$$

Producer 3 Equations

$$h_1b_{1,A}RM_{1,3} + h_2b_{2,A}RM_{2,3} + h_3b_{3,A}RM_{3,3} + h_4b_{4,A}RM_{4,3} + h_5b_{5,A}RM_{5,3} + h_6b_{6,A}RM_{6,3} + h_7b_{7,A}RM_{7,3} \geq Y_{A31} + Y_{A32} + Y_{A33}$$

$$h_1b_{1,B}RM_{1,3} + h_2b_{2,B}RM_{2,3} + h_3b_{3,B}RM_{3,3} + h_4b_{4,B}RM_{4,3} + h_5b_{5,B}RM_{5,3} + h_6b_{6,B}RM_{6,3} + h_7b_{7,B}RM_{7,3} \geq Y_{B31} + Y_{B32} + Y_{B33}$$

$$h_1b_{1,C}RM_{1,3} + h_2b_{2,C}RM_{2,3} + h_3b_{3,C}RM_{3,3} + h_4b_{4,C}RM_{4,3} + h_5b_{5,C}RM_{5,3} + h_6b_{6,C}RM_{6,3} + h_7b_{7,C}RM_{7,3} \geq Y_{C31} + Y_{C32} + Y_{C33}$$

$$h_1b_{1,D}RM_{1,3} + h_2b_{2,D}RM_{2,3} + h_3b_{3,D}RM_{3,3} + h_4b_{4,D}RM_{4,3} + h_5b_{5,D}RM_{5,3} + h_6b_{6,D}RM_{6,3} + h_7b_{7,D}RM_{7,3} \geq Y_{D31} + Y_{D32} + Y_{D33}$$

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