HOLISTIC BIOMIMICRY: A BIOLOGICALLY INSPIRED APPROACH TO ENVIRONMENTALLY BENIGN ENGINEERING

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HOLISTIC BIOMIMICRY: A BIOLOGICALLY INSPIRED APPROACH TO ENVIRONMENTALLY BENIGN ENGINEERING

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To all those too proud, stubborn or foolish to quit

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF SYMBOLS AND ABBREVIATIONS

A	Ascendancy
CI	Cycling index
e_{avg}	Average mass specific energy consumption rate for aircraft
E_{avg}	Average energy consumption rate for aircraft
f_{ij}	Material flow rate from node j to node i
h_{LHV}	Lower heating value of jet fuel
H_1	Shannon Wiener Index
H_2	Concentration
$\mathbf{H_i}$	Holons (nodes) i = 1, 2,…n
$\sum IN$	Total material inflow in a production matrix
m_a	Mass of empty aircraft
m_{bc}	Contaminant mass before cleaning
m_{curb}	Curb weight of vehicles
m_{fuel}	Mass of aircraft fuel
m_r	Contaminant mass that remains after cleaning

m_{total}	Total mass of aircraft
$\mathbf{N}^*$	Transitive closure matrix
$\sum OUT$	Total material outflow in a production matrix
p_i	Proportion of the i-th species in a habitat
P	Engine power
P_{AC}	Air-conditioner power consumption
P_c	Proportion of contaminant removed
$\overline{PL}$	Mean path length
$\overline{PL_c}$	Cycled component of mean path length
$\overline{PL_s}$	Non-cycled component of mean path length
$\mathbf{Q}^*$	Instantaneous fractional inflow matrix
Q_{cool}	Cooling capacity of an air-conditioner
r	Roughness factor
r_{max}	Maximum aircraft range
R	Sum of all trophic flows in the ecosystem
R_{ij}	Trophic flow from compartment i to compartment j

RE_k Cycling efficiency of node k

T_k Throughflow, the rate of material flowing through a node k

TST Total system throughflow

TST_c Cycled total system throughflow

v_c Cruise velocity for aircraft

x_i State variable indicating material storage (+ subscript) or retrieval (- subscript) rate for node I when conducting I-O analysis

y_{0j} Material outflow rate from node j to beyond the network

z_{i0} Material inflow rate from beyond the network to node i

γ_{lf} Surface tension

γ_{sf} Solid-fluid interfacial tension

γ_{sl} Solid-liquid interfactial tension

η_{CI} Compression ignition engine efficiency

η_{SI} Spark ignition engine efficiency

θ Contact angle

θ_R Rough surface contact angle

ρ_f Average jet fuel density

CCM	Constant comparative method
EBDM	Environmentally bendign design and manufacturing
EER	Energy efficiency ratio
EIP	Eco-industrial park
EER	Energy efficiency ratio
IBS	Integrated bio-system
LCA	Life cycle assessment
LCI	Life cycle inventory
SECR	Specific energy consumption rate

SUMMARY

Humanity's activities increasingly threaten Earth's richness of life, of which mankind is a part. As part of the response, the environmentally conscious attempt to engineer products, processes and systems that interact harmoniously with the living world. Current environmental design guidance draws upon a wealth of experiences with the products of engineering that damaged humanity's environment. Efforts to create such guidelines inductively attempt to tease right action from examination of past mistakes. Unfortunately, avoidance of past errors cannot guarantee environmentally sustainable designs in the future. One needs to examine and understand an example of an environmentally sustainable, complex, multi-scale system to engineer designs with similar characteristics.

This dissertation benchmarks and evaluates the efficacy of guidance from one such environmentally sustainable system resting at humanity's doorstep – the biosphere. Taking a holistic view of biomimicry, emulation of and inspiration by life, this work extracts overarching principles of life from academic life science literature using a sociological technique known as constant comparative method. It translates these principles into bio-inspired sustainable engineering guidelines. During this process, it identifies physically rooted measures and metrics that link guidelines to engineering applications. Qualitative validation for principles and guidelines takes the form of review by biology experts and comparison with existing environmentally benign design and manufacturing guidelines. Three select bio-inspired guidelines at three different organizational scales of engineering interest are quantitatively validated. Physical

experiments with self-cleaning surfaces quantify the potential environmental benefits generated by applying the first, sub-product scale guideline. An interpretation of a metabolically rooted guideline applied at the product / organism organizational scale is shown to correlate with existing environmental metrics and predict a sustainability threshold. Finally, design of a carpet recycling network illustrates the quantitative environmental benefits one reaps by applying the third, multi-facility scale bio-inspired sustainability guideline.

Taken as a whole, this work contributes (1) a set of biologically inspired sustainability principles for engineering, (2) a translation of these principles into measures applicable to design, (3) examples demonstrating a new, holistic form of biomimicry and (4) a deductive, novel approach to environmentally benign engineering. Life, the collection of processes that tamed and maintained themselves on planet Earth's once hostile surface, long ago confronted and solved the fundamental problems facing all organisms. Through this work, it is hoped that humanity has taken one small step toward self-mastery, thus drawing closer to a solution to the latest problem facing all organisms.

CHAPTER 1: THE CASE FOR BIOLOGICALLY INSPIRED ENVIRONMENTALLY BENIGN ENGINEERING

1.1 Motivation and Problem Definition

Environmentally benign engineering exists to support the ultimate goal of sustainable development. One often defines sustainable development as activities that provide the needs of the current generation without sacrificing the ability of future generations to fulfill their needs (Brundtland 1987). To minimize environmental impacts, most agree that environmentally benign design and manufacturing (EBDM) frameworks should promote a holistic, systems based perspective that encompasses entire product life cycles (Congress 1992, EPA 1993). Systems based perspectives allow one to grasp the magnitude and extent of environmental problems. They also give one an appreciation of the interconnected nature of engineered systems creating these problems. A proper understanding of this interconnectedness prevents one from creating partial solutions that merely transfer the burden observed in part of the system to other parts of the system. Understanding the relationships between system components also allows one to explore systemic solutions to particular problems. In other words, one gains the ability to solve problems in one part of the system by changing something in a different part of the system.

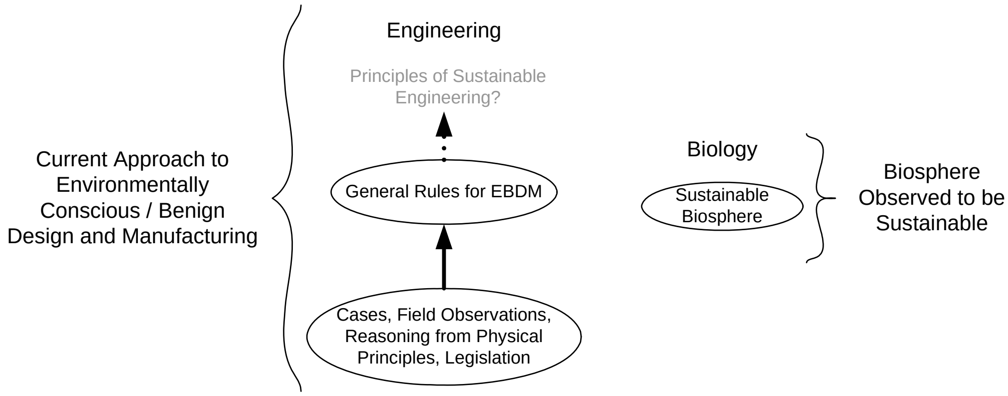

Figure 1: Current Approach to ECDM / EBDM Contrasted with Unutilized Benchmark

Current frameworks came into existence following the path diagramed on the left in Figure 1. Researchers and practitioners abstracted general rules from observations of environmental effects, product case studies, physical reasoning and even legislation. They sought to identify patterns in the data that might guide design and manufacturing away from unsustainable practices.

Unfortunately, these inductive approaches lack a known connection to a "theory of environmental sustainability." Gaps in environmental science appear as gaps in EBDM guidance. Learning from past mistakes allows one to avoid similar failures in the future, but such learning does not necessarily constitute a recipe for designing and managing environmentally sustainable products, processes and systems. Furthermore, current EBDM methods suffer from a host of technical limitations, as mentioned in Section 1.1.1.1, and as discussed in Section 1.1.1.2, limits on predictive capacity reduce the applicability of even the existing, limited methods. Therefore, one cannot guarantee that existing EBDM frameworks represent a path to environmental sustainability.

1.1.1 Cracks in Environmentally Benign Engineering's Current Foundation

Life cycle assessment undergirds many tools and methods employed by those working in the EBDM field, but despite improvements and modifications, it remains deeply flawed. In a more fundamental sense, dependence upon inductive approaches limits existing EBDM tools by reducing predictive capacity and scope of applicability. This section highlights both of these cracks in EBDM's foundation, thus motivating the research program outlined in Section 1.3.

1.1.1.1 <u>Life Cycle Assessment's Limitation</u>

LCA is the basis for many derivative environmental assessment and design guidance tools used in EBDM (See Section 2.1). The International Organization for Standards (ISO) defines LCA as, "a technique for assessing the environmental aspects and potential impacts associated with a product…from raw material acquisition through production, use and disposal" (International Standards Organization 1997). The environmental impacts of products ranging from milk to petrol have been compared using current LCA methods (Furuholt 1995, Boer 2003). A conventional LCA consists of the following steps, which are outlined in the ISO 14040-14043 standards and in SETAC's 'Code of Practice' (Consoli, et al. 1993, Jensen, et al. 1997a):

1. Goal definition and scoping - ISO 14040
2. Inventory analysis - ISO 14041
3. Impact assessment - ISO 14042
4. Improvement Assessment (SETAC term) / Interpretation (ISO term) - ISO 14043.

Unfortunately, life cycle assessment's phases suffer from a host of problems. Goal definition and scoping involve functional unit selection and assessment boundary demarcation. However, different functional units lead to different impact estimates for the same product system (Hischier, et al. 2003, Kim, et al. 2006), and alternative boundary demarcations also cause different estimates (Graedel 1998a). Such differences can confuse and complicate decision processes.

Inventory analysis requires a confrontation with, "one of the classical methodological problems in LCA…" – allocation (Russel, et al. 2005). Allocation is the assignment of environmental burdens generated by technological activities to particular product systems. It becomes problematic when multiple product systems rely upon a particular activity (i.e. petroleum refining). Multiple allocation procedures exist for situations in which more than one product system shares an activity (Ekvall, et al. 1997). Since different procedures can lead to different results, the allocation problem introduces yet more ambiguity into LCA.

Impact assessment is, arguably, the most troubled phase of LCA. Difficulties begin with the selection of environmental impact categories (i.e. global warming potential, acidification potential, eutrophication potential, etc.). Different groups advance different impact category lists (Finnveden 2000). At best, the presence of different lists sows confusion among practitioners; at worst, it suggests the possibility that important impacts are omitted during some assessments. Environmental damages occurring at sub-global geographical scales often exhibit spatial, temporal and site-specific variations, but traditional LCAs ignore space, time and place (Owens 1997, Reap, et al. 2003). Even ISO 14042 acknowledges that ignoring space and time reduces the "environmental relevance" of at least some results (ISO 2000).

LCA's final phase, interpretation, often introduces controversial valuation steps such as normalization, weighting and monetization. Even if a clear and unambiguous approach to the previous three phases existed, different valuation procedures generate different aggregated impact estimates for the same product system and potentially influence the outcome of decisions based upon these estimates. A stakeholder's preferences, not the inherent environmental character of a product system, may dictate whether LCA finds a product environmentally superior to another.

1.1.1.2 Metrics Mindset

Frosch and coauthors consider environmental metrics at the "heart of how industry defines environmental performance" and estimates "progress" (Frosch, et al. 1999). Whether rooted in LCA or some other inductive tool employed by those engaged in EBDM, measures, metrics and indicators represent snapshots of an environmental system of interest. Unfortunately, partial representations frozen in time cannot fully capture a system's underlying dynamics. Such limited representations also constrain the vision of those involved in decision processes to the near term. Their limited predictive capability and the threat of local minimums constitute a problem common to inductive EBDM approaches – the metrics mindset.

The range of potential, yet unrealized, product system states represents a design space. The search for an environmentally sustainable product system configuration represents the search for satisficing (Simon 2001) sets of design variables. Regardless of the algorithm selected to aid this search, a designer must remain cognizant of local minima. Consider the hypothetical environmental damage space presented in Figure 2. Designers manipulate design variables in an attempt to minimize the environmental impact of product systems. However, without understanding the underlying dynamics and lacking a sufficient understanding of the system's current state, designers cannot accurately represent the design space; the square with thick black lines in Figure 2 represents the limits of prediction.

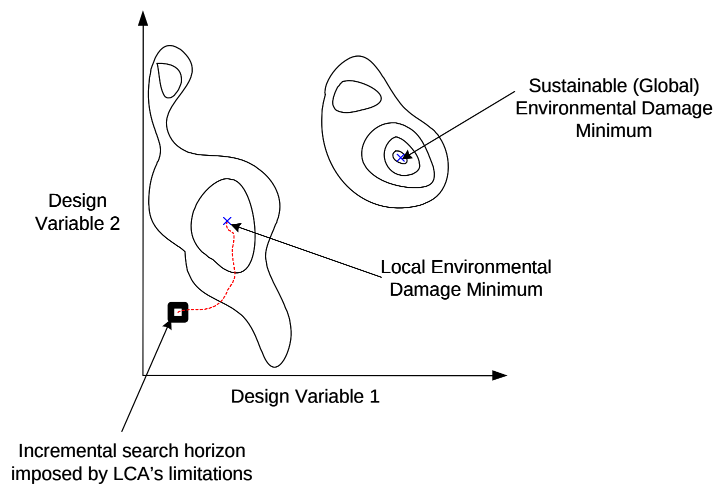

Figure 2: Potential Consequence of Using LCA to Aid Design in a Complex Environmental Space

The reader, benefiting from an omniscient perspective, can see the environmental damage contours, but designers can only see what falls within the bounds of the square. Four environmental damage minimums are apparent, but only one of the minimums is global. If one assumes for the moment that one can achieve sustainable operations by changing the two design variables to the coordinates of the global minimum, what is the likelihood of reaching the sustainable minimum through incremental improvement?

Given only snapshots of potential impacts or trends in estimated impacts, decisions executed at comparatively small time steps to decrease the unsustainability of a product system lead to local eco-efficiency maximums or local environmental damage minimums which may fall short of sustainability, as the dotted line leading from the square to a local minimum in Figure 2 suggests. Damage allowed at these minimums surpasses the amount tolerated by the environmental system in this figure and may surpass tolerable levels in practice. Worse yet, having fallen into such a minimum, a designer lacking a comprehensive view of the design space or deprived of guiding design principles may believe that further improvements are not possible.

1.2 Biomimicry's Reductive Reality

A persistent, complex, multi-scale system exists in the form of the biosphere. The three properties of the biosphere listed in the previous sentence make it an intriguing source of inspiration for a new EBDM framework. Unfortunately, current approaches to learning from nature, biomimicry or bio-inspiration, do not share the systems based perspective needed for work in EBDM.

Biomimicry literally means the imitation of life. Combination of the Greek roots *bios*, life, and *mimikos*, imitation, gives rise to the term. From bio-robotics to material science, the mimicry of life provided and continues to provide novel insights into engineering problems (Benyus 1997, Goldin, et al. 2000, Ball 2001, Beattie, et al. 2001). In robotics, one finds a focus on sensors, propulsion methods and manipulators that imitate those of organisms (Webb, et al. 2001). Investigators attempt to model and imitate the chemosensory capabilities of lobsters and the taste sense of human tongues (Toko 2000, Webb, et al. 2001). One example of a kinematical sensor emulates length and velocity detection in muscles (Jaax, et al. 2004). A device meant to mimic the bone conduction mechanics believed responsible for the sensation of food crispness also exists (Makino, et al. 2002). These are but a few examples of this line of work. Mammals, reptiles, insects and other organisms inspired over 30 years of robotics research on manipulators, grasping devices and locomotion (Waldron 2000). Considering only propulsive mechanisms and manipulators, one finds robots with tuna and cockroach kinematics (Barrett 1996, Webb, et al. 2001). In material science and engineering, one finds strong interest in biopolymers, biomineralization and self-assembly. Examples of research include work on sound adsorbing biopolymers and hydrogels with potential applications as living tissue scaffolds (Urry, et al. 2003, Vojtova, et al. 2003). In efforts to understand and replicate nature's multilayer biomineralized composites such as teeth and shells, researchers explore the deposition of thin films of calcium carbonate (Ajikumar, et al. 2003). Others explore means of forming biomineralized material morphologies using Calcite and Silica (Kim, et al. 2003, Sumper, et al. 2004). Huie provides a review of successful self-assembly efforts in nanotechnology focusing on electrostatic, chemical and biologically assisted nano-scale material creation and modification (Huie 2003).

A common thread weaves through the previous examples of biomimicry. In each case, researchers mimic particular biological technologies: taste sensation, fish locomotion, self-assembly, etc. As a result, biomimicry in engineering research and practice tends toward reductionism. In multiple domains, applied scientists and engineers work diligently to mimic a few features or functions of particular organisms or biological processes. They focus on particular technologies or elements of technologies at particular scales. They seek to transfer performance enhancing biological "technology" from the living world to the design table. This mindset views biomimicry as a tool for solving particular problems in the conceptual and embodiment phases of design. Such an approach to biomimicry adds to the knowledge in specific domains, and it provides valuable new technologies. But, by narrowing the scope of inquiry, it also limits biomimicry's applicability, particularly in the realm of environmental sustainability.

1.3 Research Questions and Hypotheses

The engineered world, some argue, might benefit from nature's guidance concerning environmental as well as traditional performance (Benyus 1997, Beattie, et al. 2001). The current, reductive mindset limits biomimicry's applicability in environmentally benign design and manufacturing to green technology development. But, can a more holistic approach to the imitation of life offer something more? These observations and this question motivate the primary question of this dissertation.

How can biomimicry guide environmentally benign engineering?

Life, the collection of processes that tamed and maintained themselves on planet Earth's once hostile surface long ago passed a critical test for environmental sustainability – time. The word "sustainable" literally means to be capable of enduring (Dictionary 1993c). Life endured for billions of years and continues to endure (Gamlin, et al. 1987). Starting with the same basic building blocks, both mankind and the rest of the living world built hierarchical systems (See Figure 3). However, one path from atoms to ecosystems is sustainable, and the other is not. It is easy, then, to understand the environmentally conscious engineer's interest in biomimicry. Learning the methods by which biotic systems reached their environmentally sustainable state might allow the creation of sustainable products, processes and systems.

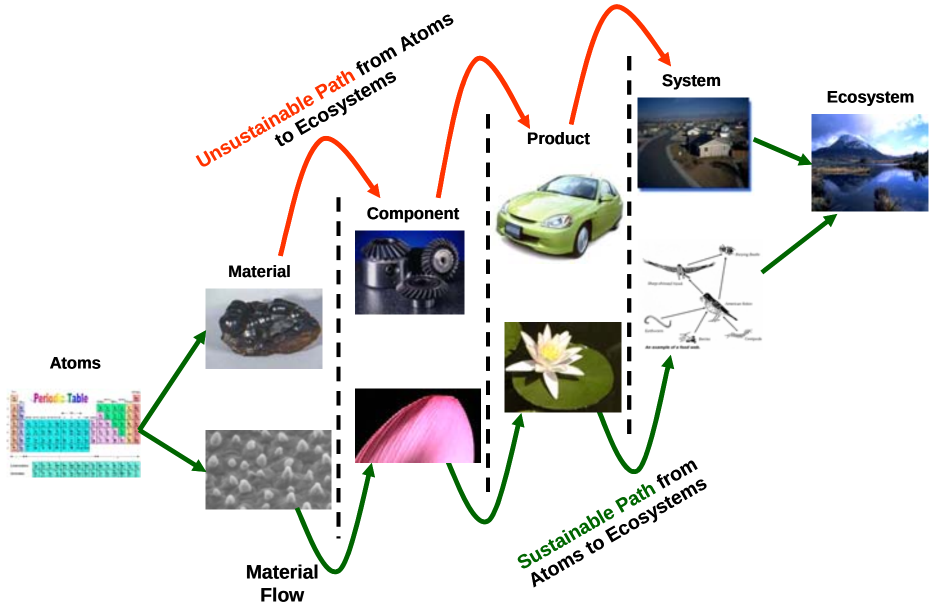

Figure 3: Systems Hierarchies in Engineering and Biology

Writing on the topic of biomimicry, Vogel observes that "emulation holds promise…" when "…one technology operates in the domain of the other" (Vogel 1998). He thoughtfully notes that biomimicry produces generally useful results when humanity's grasp of the "underlying" science is weak. When the products of engineering must interface with the biosphere, they operate in the living world's domain. Presence of the limitations discussed in Section 1.1.1 reveals weaknesses in humanity's understanding of the science and engineering needed to produce environmentally less damaging - let alone sustainable - products, processes and systems. The need for compatibility coupled with weaknesses in current environmentally conscious practice suggest an opportunity for the novel application of biomimicry.

However, the current reductive course of most biomimetic inquiry aims to transfer technology not elucidate a path to environmental sustainability. A more holistic approach appears necessary. Allen and Starr define holism as (Allen, et al. 1982):

A descriptive and investigative strategy which seeks to find the smallest number of explanatory principles by paying careful attention to the emergent properties of the whole as opposed to the behaviors of the isolated parts…

Taking the endurance of the biotic system as an emergent property, holistic biomimicry becomes the search for and application of explanatory principles within the context of engineering. Stating the proposed hypothesis succinctly:

Biomimicry in the form of a governing set of living system principles can serve as a guiding framework for environmentally benign engineering.

The search involves careful observation of the biotic system to identify a set of principles contributing to its inherent sustainability. Application involves the translation of these principles into concepts meaningful for engineers and the incorporation of these concepts in product, process, facility and other engineering design activities. Therefore, in this work, *holistic biomimicry is defined as the identification, translation and application of biologically inspired sustainability principles within the context of engineering*. Figure 4 diagrams and illustrates the contrast between this strategy and the strategy used to create existing EBDM frameworks.

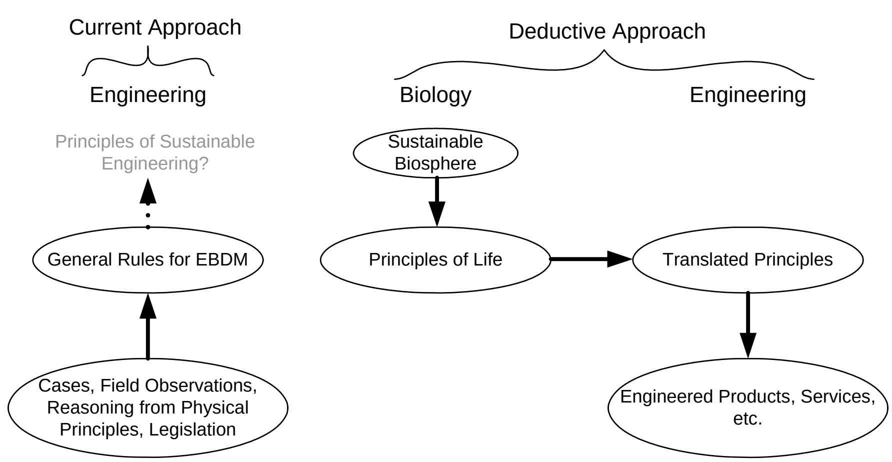

Figure 4: Current and Proposed Strategies for Constructing EBDM Frameworks

In engineering, multiple terms label the practice of learning from organisms and systems present in the biosphere. These include: bioinspiration, biomimetics, biomimicry, bionics, biognosis and others. To better situate holistic biomimicry within the lexicon of proceeding ideas, it is worthwhile to discuss the meanings and usage for some of these terms. Situation begins with statement of their common denotations.

<u>biomimetics</u> – "the study of the formation, structure, or function of biologically produced substances and materials (as enzymes or silk) and biological mechanisms and processes (as protein synthesis or photosynthesis) especially for the purpose of synthesizing similar products by artificial mechanisms which mimic natural ones" (Dictionary 2009a) OR "a branch of science in which synthetic systems are developed by using information obtained from biological systems" (Dictionary 1994a)

<u>biomimicry</u> – "the copying or imitation of a natural phenomenon's or environment's efficiency and survival mechanisms in manufacturing processes or in applied case-based reasoning" (Dictionary.com 2009)

<u>bionics</u> – "a science concerned with the application of data about the functioning of biological systems to the solution of engineering problems" (Dictionary 2009b) OR "the study of systems, particularly electronic systems, which function after the manner of living systems" (Dictionary 1994b)

<u>biognosis</u> – "the scientific investigation of life" (Dictionary 1993a)

These definitions clearly indicate that learning from the living world requires study, and two of the three state that study is meant to support synthesis by artificial means. Biognosis falls short of synthesis, stopping at "investigation." The two terms that include study and development, biomimetics and bionics, possess almost synonymous definitions. An emphasis on electronics introduced by McGraw Hill's technical dictionary is the only means of separating them. It is noteworthy that available online and print dictionaries lack a definition for bioinspiration. One might easily construct one from the roots of the word, “bio” or life and “inspire” or influence. However, bioinspiration is not currently part of the definitive lexicon.

All terms except biomimicry appear as labels for prominent journals or research groups. Consider the journal Bioinspiration & Biomimetics. This journal welcomes works that extract biological “principles and functions” and that use them to develop “basic technologies” or solve problems (journals 2009). As one might expect, the journal’s scope matches that of the definition for biomimetics. The Centre for Biomimetics at the University of Reading, the Biomimetics & Natural Technologies group at the University of Bath and the Biologically Inspired Product Development group possess statements defining their activities in terms consistent with the previous definition of biomimetics (Golden 2006, Biomimetics 2009, Bowyer 2009) . The definition used at the University of Bath is germane to this discussion.

> *Biomimetics, also known by several names, eg bionics, biognosis, is the concept of taking ideas from nature and implementing them in another technology such as engineering, design, computing, etc.* (Bowyer 2009).

Besides adhering to the common definition of biomimetics, the Bath definition declares two of the other previously defined terms as synonyms. Examination of the scope of (1) a major journal devoted to the dissemination of scholarly biomimetic research and of (2) representative research groups shows that the meanings of biomimetics, bioinspiration and bionics converge.

Biomimetics, biomimicry and bionics possess definitions traceable to those responsible for coining the terms. The engineering disciplines recognize Otto Schmitt as the originator of the word biomimetics (Bhushan 2009). Schmitt purportedly created the term while developing a biologically inspired electrical circuit known in the electrical engineering community as the Schmitt Trigger (Schmitt 1938). Schmitt defined biomimetics as, "'the mimicry of life,' or biology," and he believed that the products of this mimicry could help solve mankind's problems (Gutzmer 2005). Janine Benyus can lay claim to biomimicry which she defines as, "…a new science that studies nature's models and then imitates or takes inspiration from these designs and processes to solve human problems…" (Benyus 1997). Jack E. Steele receives credit for coining the term bionics in 1958 (Gerardin 1968). He defined it as, "…the science of systems whose function is based on living systems, or which have characteristics of living systems, or which resemble these," but in the years immediately following its initial statement, the growing bionics community began to define the term as, "…the art of applying the knowledge of living systems to solving technical problems" (Gerardin 1968). It is important to note that the meanings for these words possess the same essential elements found in later definitions. Both communicate the intent to study living systems for the purposes of imitation, and those responsible for the definitions intended to imitate in order to solve technical problems.

Usage in engineering literature conforms to the definitions found in dictionaries, used by thought leaders and advanced by engineering pioneers. Researchers apply the trio of verbs: study, imitate and solve. They study living systems with the intent of imitating, in some fashion, in order to solve technical problems. Work on the movement of bacteria provides a good example. Data on *Escherichia coli* were used to build a model of its motile behavior that was then applied to simulated target tracking problems (Kim 2008). In other work, an algorithm based on bacterial foraging optimizes power supply networks (Panigrahi 2008, 2009). Both cases illustrate the study or use of data about bacterial motion to imitate behavior in order to solve a technical problem. Turning from algorithms to robotics, Lee and coauthors contend that, "…nature provides roboticists with design ideas, while robotics research elucidates critical features that confer performance advantages to biological systems" (Lee, et al. 2008). One finds a focus on sensors, propulsion methods and manipulators that imitate those of organisms (Webb, et al. 2001). Investigators attempt to model and imitate the chemosensory capabilities of lobsters and the taste sense of human tongues (Toko 2000, Webb, et al. 2001). One example of a kinematical sensor emulates length and velocity detection in muscles (Jaax, et al. 2004). A device meant to mimic the bone conduction mechanics believed responsible for the sensation of food crispness also exists (Makino, et al. 2002). Mammals, reptiles, insects and other organisms inspired over 30 years of robotics research on manipulators, grasping devices and locomotion (Waldron 2000). Considering only propulsive mechanisms and manipulators, one finds robots with tuna and cockroach kinematics (Barrett 1996, Webb, et al. 2001). Noting nature's integral designs, some seek to create propulsive systems with imbedded sensors (Cutkosky 2009). In material science and engineering, one finds strong interest in biopolymers, biomineralization and self-assembly. Examples of research include work on sound adsorbing biopolymers and hydrogels with potential applications as living tissue scaffolds (Urry, et al. 2003, Vojtova, et al. 2003). In efforts to understand and replicate nature's multilayer biomineralized composites such as teeth and shells, researchers explore the deposition of thin films of calcium carbonate (Ajikumar, et al. 2003). Others explore means of forming biomineralized material morphologies using Calcite and Silica (Kim, et al. 2003, Sumper, et al. 2004). Still others use biological materials as templates for the deposition of more common engineering materials such as silicon carbide in the hope of achieving desired micro and meso structures more efficiently (Maddocks, et al. 2009). Huie provides a review of successful self-assembly efforts in nanotechnology focusing on electrostatic, chemical and biologically assisted nano-scale material creation and modification (Huie 2003). Bhushan provides a comprehensive overview of biomimetics as applied to engineered surfaces (Bhushan 2009). However, it is clear that material scientists refrain from mimicking in the strictest sense of the word. Rather, they recognize the "…potential for relevant lessons…" to emerge from the study of nature while remaining cognizant of "…the limitations of such lessons" (Reed, et al. 2009).

While the intent to study, imitate and solve is clear in the cited engineering literature, preferred terminology varies. Kim and Panigraphi largely eschew labels such as biomimetics or bioinspired in favor of more specific descriptors (Kim 2008, Panigrahi 2008, 2009). Some prefer to use biomimicry or biomimetics to describe their activities (Makino, et al. 2002, Jaax, et al. 2004). Others use biomimicry and bioinspiration synonymously (Lee, et al. 2008, Margaliot 2008, Cutkosky 2009). Bhushan even states that "biologically inspired design" is the same as biomimetics (Bhushan 2009). Others draw a line between the two terms, believing that profitable engineering activities benefit from natural inspiration (bioinspiration) rather than copying (biomimicry) (Bandyopadhyay 2009). Definitions can also change from author to author. Reed uses biomimetics, but he believes that materials design is best served when "…'what if' questions are informed by knowledge of biology…" yet refined by knowledge from other fields (Reed, et al. 2009). His approach is closer to inspiration than mimicry which suggests a preference for bioinspiration despite the use of biomimetics.

Considering standard definitions, the ideas of pioneers and current usage in engineering, one draws the following conclusions about the use of terms meant to denote the process of learning from nature. First, in engineering biomimetics stands as the most recognized term for the process of learning from nature. It appears in dictionaries, on the covers of journals and in the jargon of multiple engineering disciplines. Second, biomimicry carries the same meaning as biomimetics. It possesses the same Greek roots, and its denotations almost match those for biomimetics. Biomimicry also appears alongside biomimetics in technical literature. Third, terms such as bioinspiration and bionics appear to be synonyms for biomimetics. A comparison of the standard definitions of bionics and biomimetics reveals their similarity. While not always clear, multiple engineering disciplines use bioinspiration and biomimetics interchangeably. Fourth, bioinspiration is almost as common as biomimetics, but importantly, it is absent from at least three dictionaries of the English language. Therefore, biomimetics or biomimicry, its close variant, are the most appropriate terms for the work described in this dissertation.

To summarize, the use of bio-inspired principles in EBDM promises two general benefits. First, principles provide a benchmark for the environmental performance of technical systems. Principles facilitate better comparisons between technical systems and known, sustainable systems found in the biosphere. Second, properly interpreted principles encapsulate many physical relationships operating in the complex biosphere. To those engaged in EBDM, these compact models communicate biological and ecological system behaviors worth emulating and constraints worthy of respect.

This overarching hypothesis begs a number of questions. These questions and their associated hypotheses address issues associated with developing the mentioned guiding framework. Collectively, these questions serve to foster the development of a unique, holistic form of biomimicry in environmentally benign engineering design.

1.3.1 Identifying Life's Principles for Environmentally Benign Engineering

Holistic Biomimicry offers an *a priori* approach to environmentally benign engineering that differs markedly from the retrospective view offered by methods guided by LCA and other inductive tools. The mentioned a priori guidance depends upon the existence of holistic biomimetic principles. Identifying biological principles which contribute to the biosphere's inherent sustainability is the first step in building the holistic form of biomimicry stated in the overarching hypothesis. This imperative leads to the first research question.

Q.1:	What relevant principles underpin the biosphere's inherent sustainability?
H.1:	Biology literature detailing the inherent properties of living systems contains principles responsible for the biosphere's sustainability.

Starting with a rocky, elemental orb hanging in the vastness of space, life transformed Earth's surface into the comfortable environment now enjoyed by humanity, rebounding from a number of mass extinctions along the way. Biological processes at multiple scales led to and maintain this environment. While the form and manner of presentation may not appear relevant to engineering design, it is this literature that documents the history of life's development and persistence, and it is this literature which most likely contains a priori sustainability principles which one may abstract.

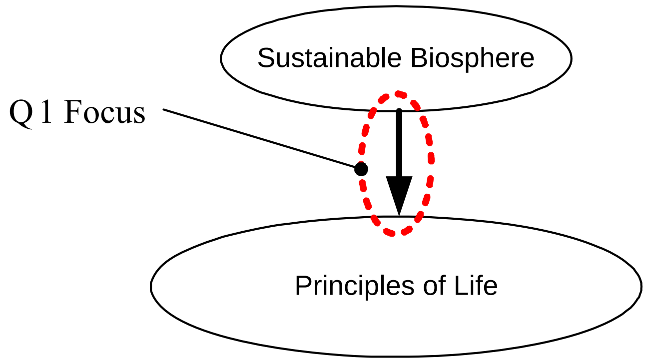

Figure 5: Focus of the First Research Question

By answering the first research question, one begins the process of building the holistic biomimicry framework diagramed in Figure 4. Specifically, one extracts life's principles by interrogating biology literature (See Figure 5).

1.3.2 Translating Principles for Environmentally Benign Engineering

As noted in Section 1.3.1, principles distilled from biology literature may not prove immediately applicable to engineering design problems. Accumulation of background information and supporting references might lead to a qualitative understanding of such relationships, but how might one quantitatively connect principle to product? This requirement leads to the second research question.

Q.2:	How can one translate life's principles into a form capable of guiding multi-scale environmentally benign design and manufacturing?
H.2:	Existing and new measures, metrics and indicators derived from life's principles will provide the necessary translation between biology and engineering.

Measures, metrics and indicators commonly represent environmental burdens and impacts in engineering design and manufacturing (Frosch, et al. 1999). Developing a suite of such figures of merit for each principle is a straightforward means of connecting qualitative statements drawn from biology with quantitative guidance for engineering design and manufacturing problems. Some existing EBE measures, metrics and indicators likely correspond with, as of yet, unidentified principles of life. And, some principles will require development of new figures of merit. Together, reordered and newly derived measures, metrics and indicators hold the potential to bridge the gap between abstracted principles and EBDM (See Figure 6).

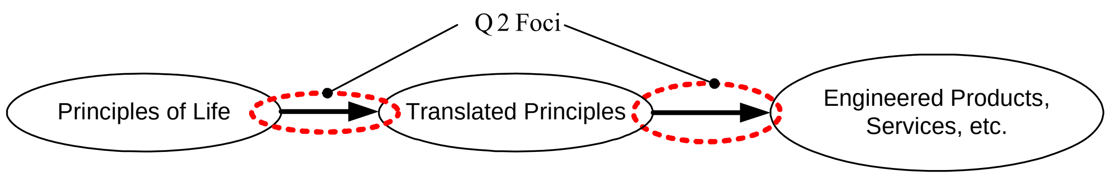

Figure 6: Focus of the Second Research Question

1.4 Validation Strategy

Holistic Biomimicry exists in a gray area between development of engineering design method and elucidation of principle. As such, it shares properties with both, and therefore, elements of both validation traditions find a place in its validation process. The validation strategy for this work draws inspiration from a design method validation approach, the Validation Square, developed by Pederson and coauthors as well as the practical guidance offered by scientific and engineering traditions (Pedersen, et al. 2000). The validation square depicted in Figure 7 attempts to establish the structural and empirical validity of design methods using qualitative analysis and quantitative examples, respectively.

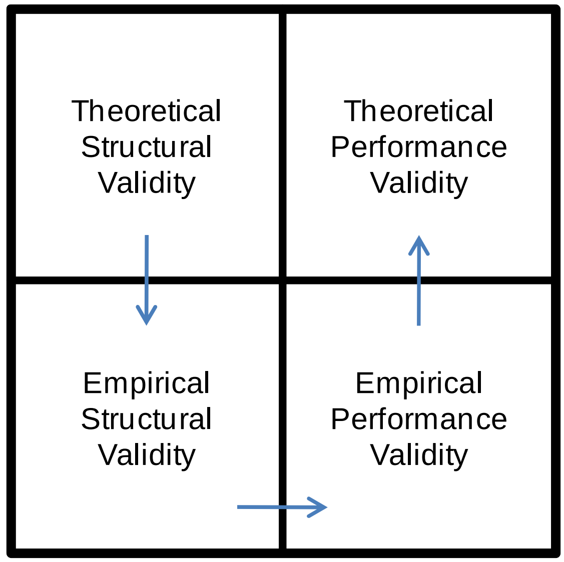

Figure 7: Validation Square (adapted from (Pedersen, et al. 2000))

Structural validity rests upon theoretical and empirical validity. Proving theoretical structural validity hinges upon establishing "construct validity" and "method consistency" (Pedersen, et al. 2000). Pederson and coauthors suggest establishing construct validity using literature support. As stated in Section 1.5.2.1, this work uses a systematic review of biology literature to identify sustainability principles, which also serves as the construct validation step. Method consistency, in this dissertation, is a simple matter of associating appropriate metrics with each principle, as discussed in 1.5.2.2. Empirical structural validity depends upon acceptance of selected example problems (Pedersen, et al. 2000). Example analysis and design problems are selected to showcase each principle's powers of prediction and guidance.

Performance validity depends upon quantitative empirical validity (Pedersen, et al. 2000). Empirical validity is, in turn, established by quantitatively demonstrating the merit of a method for representative design problems. In this dissertation, the outputs of design problems guided by holistic biomimicry are compared to designs lacking such guidance. Traditional measures of environmental performance serve as the basis of comparison. Some principles are evaluated using an analytical approach utilizing the hypothesis-test framework common to science. The outcomes of these activities provide the evidence needed to claim holistic biomimicry's empirical performance validity.

1.5 Dissertation Organization

Answering the questions outlined in Section 1.3 involves: a comprehensive literature review, extraction of biological principles, application / validation and statement of conclusions. This Section provides a synopsis of these general steps and describes the dissertation's structure. Table 1 contains an overview of the discussed structure and its connection to the dissertation's validation steps.

Table 1: Dissertation Organization Overview

Hypotheses	Validation	Applicable Chapters
H1: Biology literature detailing the inherent properties of living systems contains principles responsible for the biosphere's sustainability.	• Constant Comparative Method's coding procedures extract recurrent themes (principles) from biology literature. • Extracted principles are then reviewed by a panel of biologists.	3
H2: Existing and new measures, metrics and indicators derived from life's principles will provide the necessary translation between biology and engineering.	• An engineering literature review compares common EBDM themes with those present in the bio-inspired sustainable engineering guidelines. • Metrics embodying the essence of the extracted principles are put to the test in experiment and design related scenarios. Results are evaluated using conventional environmental assessment techniques.	3-6

1.5.1 Literature Review

Chapter 2 reviews pertinent literature in environmentally conscious design, and environmental assessment. The second chapter uses a discussion of each of these topics to set the intellectual case for holistic biomimicry on firm ground. Beginning with a review of environmentally conscious design and manufacturing literature, it illustrates the dependence of current tools and methods upon LCA and suggests ways in which a principled approach might enhance current practice. It increases the breadth and depth of Section 1.1.1.1's motivational discussion about LCA's limitations, thus underscoring the need for an additional source of design guidance. Chapter 2 concludes with a summary of the key problems unearthed during the literature review that motivate the formation of the holistic biomimetic framework built and tested during the remainder of this dissertation.

1.5.2 Building Holistic Biomimicry

Chapter 3 establishes a foundation for holistic biomimicry by identifying a set of potential principles and associated metrics at multiple scales. Engineering guidelines and supporting measures, metrics and indicators that embody the essence of the biologically inspired, sustainability guidelines are the chapter's primary outputs.

1.5.2.1 <u>Extraction of Living Systems Principles and Development of Holistic Biomimicry</u>

Literature in biology, ecology, paleobiology, and evolutionary biology are gathered for organizational scales of strategic interest. These scales include the sub-cellular, cellular, organal, organismic and ecological. Once gathered, Constant Comparative Method is used to code the literature at each scale (Strauss, et al. 1994). Used primarily in the social sciences to extract unifying concepts from interview data (Glaser, et al. 1967), Constant Comparative Method's coding procedures are used to identify categories and abstract concepts in the collected biology literature. The resulting code notes reveal recurrent and dominant themes, the unifying concepts that are life's sustainability principles. This chapter outputs a list of life's characteristics, potential principles.

1.5.2.2 Translating and Operationalizing Principles

Bridging the gap between biology and engineering is the second major step in the process of building holistic biomimicry. Translation of biological sustainability principles begins with qualitative restatement in an engineering context. Having cast principles in an engineering context, one relates them to engineering design and manufacturing by developing suites of measures, metrics and indicators capable of serving as goals in design problems. One obtains these measures, metrics and indicators by first comparing the principles with existing EBDM guidelines. Figure 8 illustrates the three types of mathematical formalizations one may potentially produce using the approach in this chapter.

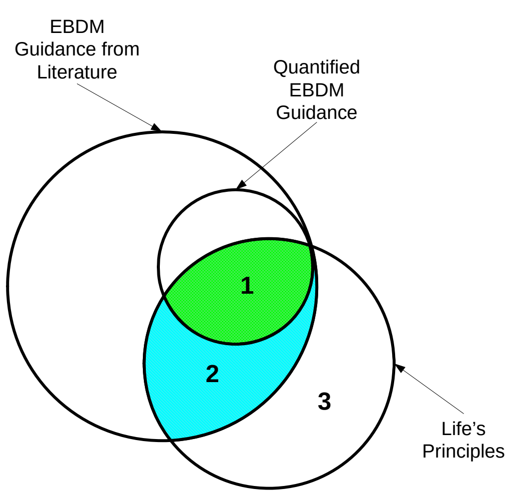

Figure 8: Types of Formalization

Where biological principles and current guidelines prove similar (1), one reorganizes these figures of merit found in EBDM under the holistic biomimicry framework. Where guidelines lack quantification (2), one may find sufficient biological inspiration to quantify corresponding guidelines. One fills gaps in the EBDM guidelines (3) by porting mathematical statements associated with the principles found in biology. Formalized engineering principles and supporting measures, metrics and indicators that embody the essence of the biologically inspired sustainability principles are this chapter's outcome.

1.5.3 Initial Validation of Life's Principles

The latter part of Chapter 3 also contains the first part of the validation process. It describes a biology panel review process as well as validation using a literature survey grounded in constant comparative method.

1.5.3.1 Biologists' Review

First, characteristics identified in and supported by literature in Chapter 3 are reviewed by a specific set of biologists (See Table 2).

Table 2: Biology and Biomimicry Experts

Expert	Domain	Institution
Dayna Baumeister, Ph.D.	Biomimetics, Biology	Biomimicry Guild
Steven Vogel, Ph.D.	Biology	Duke University
Marc Weissburg, Ph.D.	Biology	Georgia Institute of Technology

This panel of experts will be asked to judge the reasonableness, bias in interpretation and general validity of extracted biological principles. A set of biologically inspired sustainability principles supported by both literature and expert review emerges from the first validation task.

1.5.3.2 Comparison with Environmentally Benign Design and Manufacturing Literature

The second step in the third chapter's preliminary evaluation effort involves a comparison between the biological sustainability principles and generally accepted EBDM guidelines. Constant comparative method is used extract EBDM guidelines and concepts. Constant comparative method is a qualitative research technique used to find similarities and differences between segments of data (Merriam 1998). Similarities and differences are in turn used to identify categories and category properties. Data segments drawn from approximately 100 conference articles, journal papers and books dealing with EBDM subjects such as design for environment, environmentally conscious design and manufacturing, industrial ecology and inverse logistics are analyzed. After using this method to generate categories for EBDM guidance literature, these categories are

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d Dimensions □ PAGEREF _Tocuantitative Validation of Holistic Biomimicry

1.5.4 Quantitative Validation of Holistic Biomimicry

Chapter 4-6 quantitatively validate the principles extracted and initially validated in Chapter 3 by applying them to situations of engineering interest. Both analysis and synthesis problems are represented. The results of these applications are evaluated using environmental measures to determine whether the selected principles promote environmentally superior outcomes. Chapter 4 uses experiments of relevance to industrial and commercial cleaning situations to quantify the environmental efficacy of the first principle. In Chapter 5, analysis of specific energy consumption rates for products and human behavior lends support to the validity of the second principle. To investigate principles impacting larger scales, Chapter 6 explores similarities between industrial resource flow networks developed to reduce consumption and pollution and resource flow networks found in the biosphere.

1.5.5 Holistic Biomimicry in Review

Chapter 7 discusses hypotheses stated in Chapter 1 in light of the achievements in Chapter 2-6. It reviews the successful principle extraction process found in Chapter 3, and it summaries arguments supporting the validity of the extracted principles found in Chapter 4-6. It also lists contributions, limitations and potential future directions associated with this research. The journey to this closing chapter begins with a detailed inquiry into the failings of EBDM's current theoretical framework, the topic of Chapter 2.

CHAPTER 2: EXAMINING ENVIRONMENTALLY BENIGN ENGINEERING'S FLAWED FOUNDATION

Chapter 2 reiterates and strengthens the central arguments presented in Section 1.1 of Chapter 1. The opening sections of the previous chapter introduced arguments in favor of Holistic Biomimicry's development while highlighting EBDM's dependence upon LCA and LCA's weaknesses. Drawing from literature reviews of environmentally benign design & manufacturing (EBDM) and life cycle assessment, Chapter 2 clearly illustrates the mentioned connection between EBDM and LCA while delineating LCA's many weaknesses. It proceeds to discuss the consequences of building EBDM guidance on LCA, contrasting the current situation with one based on a more principled approach. Altogether, it sets the stage for development of Holistic Biomimicry in Chapter 3.

2.1 LCA as EBDM's Foundation

This opening section begins to build the argument for a second foundation for EBDM by revealing this discipline's dependence upon LCA and more narrowly focused environmental assessment techniques. It accomplishes this task by citing examples of LCA's influence and use in EBDM research, industrial practice and even policy.

2.1.1 Overview of Life Cycle Assessment

To understand EBDM's dependence upon LCA and related methods, one must first understand LCA. This section provides the requisite understanding by briefly reviewing LCA's purpose and structure.

According to the International Organization for Standards (ISO), LCA is a method used to assess environmental aspects and impacts of product and service systems

(ISO 1997, 2006a). One divides LCA into four distinct though interdependent phases (See Table 3).

Table 3: Description of Each LCA Phase

#	Phase	Description
1	Goal and Scope Definition	LCA goal and scope definitions contain information about the application, reason for the study, intended audience and extent of the inquiry.
2	Inventory Analysis	Inventories define and quantify the flow of material and energy into, through and from the specified system (ISO 1998, 2006b).
3	Impact Assessment	Impact assessment assigns inventory data to different environmental effect categories (classification) and then models their influence within each category to estimate environmental impacts (characterization).
4	Interpretation	As the name suggests, one draws conclusions and formulates recommendations based upon inventory data, impact assessment data and potentially weighted preferences during the interpretation phase.

2.1.2 LCA and EBDM Research

LCA's influence upon EBDM manifests itself most clearly in EBDM research, especially method development. Lessons learned from past life cycle assessments or analyses that incorporated partial LCAs often appear as guidelines or guiding themes in proposed EBDM methods. Injunctions to improve energy efficiency, reduce / eliminate toxic materials and recycle other materials are especially popular. Some methods even incorporate complete LCIs or LCAs into the design process.

Attempts to codify and make operational lessons from LCAs or more narrow environmental analyses constitute the majority of EBDM methods. These methods generally counsel designers to reduce material and energy use while increasing material reuse. As Szczerbicki's overview of the design for environment concept (DfE) reveals, design guidelines such as recyclability, energy reduction, and emissions reduction focus upon increasing material cycling, reducing energy usage and avoiding toxic releases, respectively (Szczerbicki, et al. 2004). Though not explicit, the reasons for choosing these foci are clearly related to impact categories found in LCA. Explicit applications of LCA elements appear in multiple design methods spanning the continuum of the design process from requirements formulation to detail design. Working in the requirements phase, Rounds developed environmental issues taxonomies that depend upon life cycle impact categories such as global warming (Rounds, et al. 2002). Fargnoli's combination of Quality Function Deployment for the Environment (QFDE) and EcoDesign PILOT (Product Investigation Learning and Optimization Tool) relies upon LCA related tools such as EcoIndicators 95 and 99 to estimate environmental impacts (Fargnoli 2003). One disassembly sequence optimization tool uses MET (Material-Energy-Toxicity) indicators based on LCA calculations as environmental objectives (Knight, et al. 2002). The Quotes for environmentally Weighted Recyclability and Eco-Efficiency (QWERTY/EE) tool uses LCA scores to calculate end of life values for products (Huisman, et al. 2003). A life cycle inventory analysis is used to inform and evaluate the redesign of an automotive instrument panel (Keoleian 1998).

Though less common, EBDM methods also use LCA to guide the design process. Jofre and coauthors' Eco-evolution strategy specifically calls for LCA (Jofre, et al. 2003). Jeswiet and Hauschild believe that decisions in the design phase "…must be supported by an LCA as early as possible, if the product is to have minimal impact on the environment" (Jeswiet, et al. 2005).

2.1.3 LCA and EBDM Practice

LCA influences EBDM practice by guiding product design in corporations and by informing governmental policies. A number of companies direct their attention toward energy, material flows and toxic substances. These subjects, as mentioned in the previous section, partially trace there roots to life cycle impact categories or more narrow environmental assessments. In semiconductor manufacturing operation and product design, Intel practices DfE to reduce toxic substance use and energy consumption (Brady, et al. 2003). Sun Microsystems employs DfE to improve energy efficiency, increase material cycling and reduce the use of "substances of concern" (Shiovitz, et al. 1997). An electronics commodities manufacturer focuses on material cycling by working to improve recycling and reuse (Matthews, et al. 1997). Finally, a survey of Swedish companies engaged in environmentally conscious design revealed that LCA or a related impact assessment tool was employed by all respondents, and the "best practice" companies used LCA (Ritzen, et al. 2001).

Governments also tend to focus on energy, material cycling and toxic or potentially toxic substances when preparing rules and legislation dealing with products. The European Union's WEEE and ROHS Directives mandate the take back of electronics and elimination of hazardous substances from electronics, respectively (O'Neill 2003). Masera argues that policies promoting eco-design focused upon the reduction of resource intensity and hazardous substances are essential for the development of small and medium enterprises in developing countries (Masera 2003). Such laws and policy recommendations exist in part because the material consumption and substance emissions they are meant to curb increase impacts in established life cycle impact categories.

2.2 Foundational Weaknesses: A Review of Problems in LCA

Current EBDM methods clearly rely upon LCA, but how strong is this foundation? This section briefly describes LCA's structure and then proceeds to identify and discuss its problems in detail. The problems are organized by the LCA phase in which they occur.

2.2.1 Structure of Life Cycle Assessment

According to ISO, LCA is a method used to assess environmental aspects and impacts of products (ISO 1997, 2006a). In ISO 14040 the word "product" refers to both product and service systems. Environmental impacts generated by all parts of a product's life cycle, from acquisition of materials through manufacture to recovery or disposal, are considered. One divides LCA into four distinct though interdependent phases: goal and scope definition, inventory analysis, impact assessment and interpretation (See Figure 9). . This section briefly describes each of these phases.

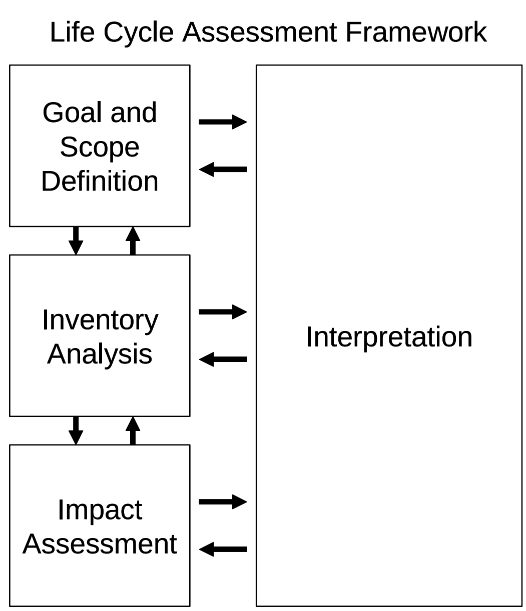

Figure 9: Life Cycle Assessment Phases

2.2.1.1 Goal and Scope Definition

A properly formulated goal in LCA contains four components. Quoting ISO 14040 2006 E, "…an LCA states [1] the intended application, the [2] reasons for carrying out the study, [3] the intended audience…and [4] whether the results are to be used in comparative assertions…disclosed to the public" (ISO 2006a).

Scope definition attempts to set the extent of the inquiry as well as specify the methods used to conduct the inquiry in later phases. It defines the extent by selecting product systems studied, identifying associated functions, establishing functional units, setting product system boundaries and prescribing report type and format. It specifies allocation procedures for the inventory phase, and it dictates impact types considered as well as impact assessment methods. It also influences multiple subsequent phases by stating assumptions, limitations, required data, acceptable data quality and the type of critical review. ISO emphasizes that, "The scope should be sufficiently well defined to ensure that the breadth, depth and detail of the study are compatible and sufficient to address the stated goal" (ISO 2006a).

2.2.1.1 Inventory Analysis

In inventory analysis, one defines and quantifies the flow of material and energy into, through and from a product system (ISO 1998, 2006b). The analyzed flows include input resources as well as output wastes for all life cycle stages. Data generated and accumulated during inventory analysis provides the foundation for life cycle impact assessment as well as some interpretations. Boundaries, allocation procedures and data quality significantly influence the comprehensiveness and value of inventory data passed to these later LCA phases.

2.2.1.2 Impact Assessment

Conversion of inventory data into environmental impact estimates is the primary objective of the impact assessment phase. One divides this process into classification and characterization (ISO 2000a, 2006b). In classification, one assigns burdens identified during the inventory to different environmental impact categories. Having classified inflows and outflows, one then characterizes their contributions to environmental problems by modeling them within environmental categories.

2.2.1.3 Interpretation

In a sense, interpretation occurs during each of the three previous phases, as Figure 9 indicates. One interprets inventory and impact modeling decisions in light of the goal and scope. Conversely, one contemplates changes in the original goal in light of the realities of gathering inventory data or characterizing these data in the impact phase. Interpretation does exist as a distinct phase, however. During this phase, one draws conclusions and formulates recommendations based upon inventory data, impact assessment data and potentially weighted preferences.

2.2.2 Goal and Scope Problems

Major problems in goal and scope definition occur as a result of three methodological choices. When comparing two or more different product systems in an LCA, functional unit definition and assessment boundary selection give rise to several difficulties. Additionally, the exclusion of social and economic aspects holds implications for LCA of which practitioners and researches should be aware.

2.2.2.1 Functional Unit Definition

Functional units measure the functional performance of product systems (International Standards Organization 1997). They "provide a reference to which the inputs and outputs are related… [and] …to ensure comparability of LCA results." Adequately selecting a functional unit is of prime importance because different functional units could lead to different results for the same product system (Hischier, et al. 2003, Kim, et al. 2006).

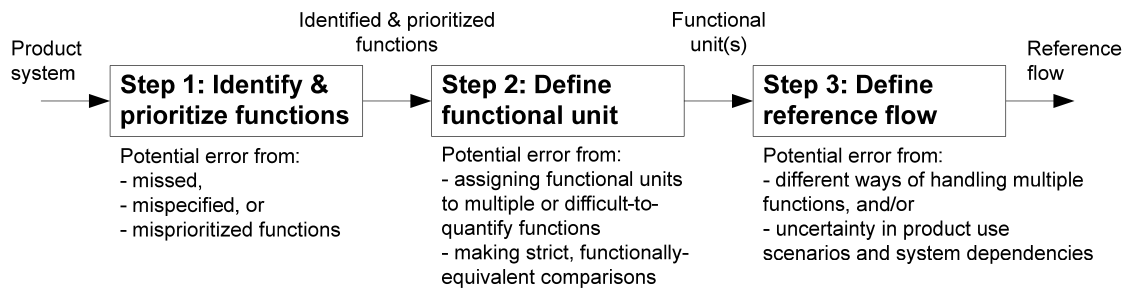

Figure 10: Potential Sources of Error Related to the Functional Unit

Unfortunately, multiple potential sources of error can diminish confidence in the appropriate selection of a functional unit. As shown in Figure 2, error can stem from inaccurate reflection of the product system reality when identifying and prioritizing functions, defining the functional unit or defining the reference flow.

Many products have multiple functions (e.g., Internet, PDA, etc.) even though most products tend to have a primary overall function. For instance, a passenger car primarily moves people from point A to point B. However, moving people in a smoother and quicker sports car adds additional and arguably relevant sub functions that are somewhat different than those of a minivan or a midsized sedan. To make comparable LCAs, it is important to consider these other sub functions when dealing with these types of products. Not identifying, decomposing, specifying and/or prioritizing these functions appropriately with respect to a study's goal and scope might yield a functional unit that reflects reality poorly.

In the second step of defining functional units, errors can arise when (1) assigning functional units to multiple functions, (2) carrying out strict, functionally equivalent comparisons and (3) when handling non-quantifiable or difficult-to-quantify functions (Cooper 2003). The difficulty with assigning functional units to multiple functions is that various potential functional units may not address all functions, as is the case in metal cleaning industrial processes (Finkbeiner, et al. 1997, Ruhland, et al. 2000). The question for the LCA practitioner then becomes, "Which functional unit should one select and/or how does one appropriately assign them to each function?" Cooper noted three ways of handling this problem (Cooper 2003), which might conceivably lead to different LCA results. With strict, functionally equivalent comparisons there is a danger that reality is not reflected well. A functional unit used in a LCA study that compared the environmental impact of getting the news from different media (newspaper, TV and the Internet) illustrates this problem (Hischier, et al. 2003). In the study, the first functional unit strictly compared the impact of getting one news story. For the newspaper, only the mass of the piece of paper containing the news story was compared against the other media! Obviously, this strict functional comparison skews the results by ignoring the fact that people do not get the newspaper in that fashion. Finally, when dealing with nonquantifiable or difficult-to-quantify functions one has to define functional units that serve as proxies or are more subjective, and as a result, they are less comparable. Examples of these latter types of functions include product aesthetics and the entertainment or learning a child gets from playing with a toy.

In the last step, error can arise from different ways to allocate reference flows to functional units (which will be addressed in Section 2.4.1) and what Cooper calls product lifetime, performance and system dependency issues (Cooper 2003). Product lifetime and performance issues refer to uncertainties arising from different product use scenarios that affect the assumed lifetime and performance of the product and as such add variability or change the reference flow (Cooper 2003). System dependency issues refer to part-specific changes that affect other parts of the product system and as a consequence the whole system performance. The significance of these issues is that they can degrade the accuracy of the reference flows associated with the selected functional unit and thus decrease confidence in LCA results.

2.2.2.2 Unit Process Boundary Selection

Boundary selection demarcates the physical, functional and temporal extent of a LCA study. These boundaries can be defined for the interface between: technological systems and nature, the geographical area and time horizon of interest, production of capital goods and the life-cycle stages and unit processes of the relevant product systems (Tillman, et al. 1994). In this section, boundary selection of unit processes will be addressed. Section 2.2.4.5 addresses time horizon boundary selection.

The basic problem centers on justifying one's LCA study boundaries based on a more objective, repeatable and scientific basis given time and resource constraints (Raynolds, et al. 2000a, Suh, et al. 2004). In other words, this entails considering the right amount of breadth and depth in one's boundary selection to inspire enough confidence in the interpretation of the LCA results. The danger of not selecting appropriate boundaries is that LCA results may either (a) not reflect reality well enough and lead to incorrect interpretations and comparisons (Lee, et al. 1995, Graedel 1998b) or (b) provide the perception to the decision maker that it does not reflect reality well enough and thus lower his/her confidence in making decisions based on the results. A recent example of this problem can be observed in the debate surrounding the energy balance of ethanol where the selection of boundaries (such as the inclusion of corn-based ethanol coproducts or energy from combustion of lignin in cellulosic ethanol) can change the results significantly (Farrell, et al. 2006, Hammerschlag 2006). Another example is ignoring maintenance and auxiliary activities such as floor cleaning, stripping and waxing, which are likely to release more VOC emissions (by several orders of magnitude) than the release occurring during a floor's 72 hour post-installation period (Lent 2003).

2.2.2.2.1 Problems with ISO 14041's Approach to Boundary Selection

To address the boundary selection problem ISO 14040:2006(E) standards recommend that the decision to select "elements of the physical system to be modeled" be based on: the goal and scope of the study, the application and audience, assumptions, constraints and some "cut-off criteria" that is "clearly understood and described" (ISO 2006a). The recommended "cut-off criteria" includes the contribution of the element to the total mass, energy or environmental relevance of the studied system. Overall, it suggests that an initial system boundary be selected and that iterative refinements be made by including new unit processes shown to be significant via sensitivity analysis (Suh, et al. 2004).

Many researchers criticized the amount of subjectivity allowed by the ISO standards, which could lead to less confidence in comparative LCA study results (Suh, et al. 2004). Specifically, various researchers argued that a cutoff is difficult to justify even when using ISO's criteria (Raynolds, et al. 2000a, Suh, et al. 2004). For instance, the following criticisms have been put forward by Suh and coauthors (Suh, et al. 2004):

(1) "there is no theoretical or empirical basis that guarantees that a small mass or energy contribution will always result in negligible environmental impacts,"
(2) some input flows bypass the product system and do not contribute mass or energy content to the product,
(3) "environmental impacts by inputs from service sectors cannot be properly judged on the basis of mass and energy," and
(4) while the individual inputs and outputs cutoff may be insignificant their total sum might change the results considerably.

Essentially, a boundary selection cutoff introduces a truncation error. A cutoff ideally would be based on the percentage of an aggregated impact score and/or different impact category indicators of interest. Using this cutoff is, however, very difficult in practice because it requires that the LCA practitioner have a perfect, holistic knowledge of all the possible effects a decision might have on the product system and consequently on the impacts of interest. To reach a reasonable approximation of this perfect, holistic knowledge a LCA practitioner needs to have access to relevant data and LCA studies or to be focusing on a simple product system. The first set of conditions will not hold for new technologies (e.g., nano technologies) or when a study report uses undisclosed confidential LCI data. Additionally, one might ask, if a practitioner has gathered all the data needed to establish a cutoff, why not use all of it?

2.2.2.2.2 Problems with Other Approaches to Boundary Selection

In addition to ISO's approach, several other researchers have proposed or identified general ways to address the boundary selection problem. These approaches fall into four categories: qualitative or semi-quantitative approaches, quantitative approaches guided by data availability, quantitative process-based approaches that use more refined cutoff criteria (Raynolds, et al. 2000a, 2000b) and input-output (IO) based approaches (Hendrickson, et al. 1998, Suh 2004, Suh, et al. 2004, Hertwich 2005, Suh, et al. 2005).

Raynolds and coauthors examined the first two types of approaches and criticized them for being highly subjective, unrepeatable or unscientific (Raynolds, et al. 2000a). Process-based approaches that use more relevant cutoff criteria and progressively span outwards to include more unit processes on the other hand, while being more rigorous and repeatable, have been shown to yield potentially high truncation errors in the fossil fuel consumption of upstream production processes of many commodities (Lenzen 2000). They also dramatically increase the data needs as the boundary expands. In his study, Lenzen showed that for fossil fuel consumption of various commodities in Australia errors ranged from 9% to 100% of the total using IO Analysis (Lenzen 2000). Additionally, using process-based approaches usually excludes capital goods, which some researchers have recently found can have a significant effect on environmental impact (Mongelli, et al. 2005, Frischknecht, et al. 2007). The limitations of process-based approaches led many researchers to explore IO LCA-based approaches as a more comprehensive and faster way of selecting boundaries.

IO LCA-based approaches have become popular in the last decade or so. A notable example is Carnegie Mellon's well-known Environmental Input-Output Life Cycle Assessment (EIO-LCA), which has been used by thousands of users from many different countries (Matthews, et al. 2001). Other IO LCA-based methods include the so-called hybrid approaches discussed by Suh and coauthors (Suh, et al. 2004). However, this family of IO LCA-based methods, in general, suffers from the following difficulties:

- The IO portion assumes that the amounts of imported commodities to the product system under study are negligible or that they come from countries with similar production technologies and economic structures (Suh 2004, p. 456), an assumption that Lenzen has conjectured could be off by a factor of three for some commodities[1] and which sounds questionable when considering that many products come from developing countries that have different electricity grid mixes, production technologies and overall economic structures.
- There is lack of applicable, well-balanced sectoral environmental data in most countries that can be correlated with economic data (Suh, et al. 2005).
- The IO-based data is usually several years older than process-based data; so it may be somewhat outdated for industry sectors that change technologies often.

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[1]Calculated from the difference in the energy multiplier to assemble (4 MJ/$) and produce vehicle and parts (12 MJ/$) (Lenzen 2000, p. 137).

- The IO-based data is usually aggregated for industries and commodities, thus diminishing the resolution capability of the IO analysis when compared with more detailed LCAs.
- The IO-based data assumes companies are perfectly homogeneous, meaning that they produce only one commodity and as such there is an allocation error.
- Some assume that monetary and physical flows are equivalently proportional amongst different industries, whereas the proportionality constants or multipliers vary between and within industries (Lenzen 2000).
- There is some uncertainty in the economic data collected from surveys to create the national economic IO tables (Lenzen 2000).
- Many IO LCA-based methods do not consider "gate-to-grave" industrial processes so they carry a truncation error themselves. Some researchers have claimed this error may be negligible in many instances (Lenzen 2000, Peters, et al. 2006), but other researchers caution that a quick elimination without further study may lead to neglecting significant unit processes (Suh 2006).
- Many IO LCA-based methods do not seem to consider the recycling (Bailey, et al. 2004a, b) or remanufacturing industry sectors (Ferrer, et al. 2000).
- It is unclear where the border between the IO-based and process-based data should be drawn when using integrated hybrid analysis (Suh, et al. 2004) and if data should be fed back to the IO-based assessment at all (Hertwich 2005).

2.2.2.3 Life Cycle Costs and Social Impacts

In addition to environmental impacts, product systems cause economic and social impacts during their life cycles as well. LCAs, however, have traditionally focused only on their environmental impacts (ISO 2006a, 2006b). As a consequence, some researchers note that, "…recommendations based on LCA fail to address possible trade-offs between environmental protection and both social and economic concerns in the product life cycle" (Dreyer, et al. 2006). From a sustainable development perspective, this can limit the capability of LCA to support decisions from both the perspective of sustainable production (i.e., companies desiring to be more sustainable) and sustainable consumption (i.e., governments developing policy to reduce unsustainable consumption trends) (Hertwich 2005). From a purely economic perspective Norris notes that the consequences of not integrating environmental and economic assessments can be missed opportunities or limited influence of LCA for decision making, especially in the private sector (Norris 2001). This is because analysts are less able to capture relationships between environmental and cost consequences of alternative decisions.

Table 4: Difficulties in Integrating Social Aspects and LCC with LCA

	Problems	Reference
Social	No consensus on how to integrate and calculate social impacts of products since social impact methodologies are still in their infancy	(Rebitzer, et al. 2003a, Hunkeler 2006)
	More than 200 societal midpoint impact indicators exist, which may lower probability of obtaining agreement on their selection and valuation in actual use	(Hunkeler, et al. 2005, Hunkeler 2006)
	Most impacts on people are independent of the physical processes that make the product and more dependent on company behavior and as such the "relation of the impacts to the product… is no longer straightforward"	(Dreyer, et al. 2006)
	Integrating social impact assessment qualitative approaches and data with LCA may be problematic	(O'Brien, et al. 1996)
	Data needs are greatly increased with non-environmental, company-specific data or region-specific data	(Dreyer, et al. 2006, Hunkeler 2006)
Economic	LCC analysis is not within the scope of developed LCA methodology, or properly addressed in traditional LCA tools, or by ISO 14040	(Norris 2001)
	"…there is neither scientific nor procedural agreement between the various stakeholders regarding [LCC] terminology, methodology, data formats, reporting, etc."	(Rebitzer, et al. 2003b)
	Disagreement on how to handle externalities in light of taxes and subsidies in order to avoid double counting (e.g., carbon taxes)	(Rebitzer and Hunkeler 2003)
	Disagreement on how to assign costs to different stakeholders (e.g., the cost to the consumer buying a product is the revenue of a company)	
	Disagreement on how to estimate and discount future costs and revenues	
	How to align data per functional unit with financial data	(Hunkeler and Rebitzer 2005)
	How to use the same system boundaries (e.g., the time horizon of an LCC might be shorter than the one assumed for a LCI and LCIA)	(Norris 2001, Hunkeler, et al. 2003, Rebitzer, et al. 2003a)

In response, various researchers have tried to resolve this problem by finding ways to integrate LCA with elements and methodologies for social impact assessment (O'Brien, et al. 1996, Dreyer, et al. 2006, Hunkeler 2006) and Life Cycle Costing (LCC) (Emblemsvag, et al. 2001, Norris 2001, Hunkeler, et al. 2003). Unfortunately, integrating LCC and LCA is difficult, but probably even more so when integrating social assessments (Hunkeler, et al. 2005). Integration attempts are fraught with difficulties summarized in Table 4. Clearly, more research is needed to determine the extent to which it is feasible, valid and beneficial to integrate LCA with LCC and emerging social impact methodologies in light of the new problems brought by integration.

2.2.2.4 Alternative Scenario Consideration

"A scenario in LCA studies is a description of a possible future situation relevant for specific LCA applications, based on specific assumptions about the future, and (when relevant) also including the presentation of the development from the present to the future" (Pesonen, et al. 2000). Some examples of scenarios that could be used in a LCA study include end-of-life scenarios (e.g., 20% landfill, 40% open-loop recycling, 40% incineration), changes in technology (e.g., from organic solvent-based to aqueous-based cleaning), etc. (Pesonen, et al. 2000). Obviously, the scenarios a LCA practitioner assumes for the LCA study will influence the results. In fact, the scenarios considered will influence all the following phases of LCA. For these reasons, it is important to select appropriate scenarios.

The inherent difficulty with any formal scenario analysis framework is that of trying to predict with confidence the future. As Smil notes, "…for more than 100 years long-term forecasts of energy affairs—no matter if they were concerned with specific inventions and subsequent commercial diffusion of new conversion techniques or if they tried to chart broad sectoral, national, or global consumption trends—have, save for a few proverbial exceptions confirming the rule, a manifest record of failure" (Smil 2003). Given that this "record of failure" just focuses on energy affairs, any LCA practitioner should pause and carefully reflect on the scenarios selected and the level of detail used in predicting the potential scenario conditions since they may “engender false feelings of insight…” (Smil 2003).

Other researchers have noted some practical problems associated with the consideration of scenario alternatives. For example, some have noted that LCA studies usually do not consider the “zero” or null alternative (Hauschild, et al. 2000b). The “zero” or null alternative means the scenario where the decision being evaluated is not carried out (i.e., the “business as usual” scenario). Another issue that has been noted in the literature is the fact that the scenarios underlying LCA studies are often not explicitly defined (Pesonen, et al. 2000).

2.2.3 Life Cycle Inventory Problems

Problems specific to life cycle inventories revolve around material flow, energy flow and process modeling. Where the goal and scope phase presented problems associated with setting study parameters, the inventory phase presents problems associated with finding and setting modeling parameters. First and foremost among these is the problem of allocation. A secondary, though important problem, is that of local technical uniqueness. Data quantity and quality problems are discussed in Section 2.2.6.

2.2.3.1 Allocation

The allocation problem has the distinction of being called one of the most controversial issues of LCA (Weidema 2001, Rebitzer, et al. 2004) and “one of the classical methodological problems in LCA" (Russel, et al. 2005). Allocation refers to the procedure of appropriately allocating the environmental burdens of a multifunctional process[2] amongst its functions or products. Thus, from this perspective, the allocation problem is one of determining how much of the environmental burdens caused by the multifunctional process should be apportioned to each product or function even though other researchers have suggested a different definition[3] (Heijungs, et al. 1998). Obviously, arbitrary allocations could lead to incorrect LCA results and less preferable decisions based on those results. The existence of many proposed allocation solutions compounds this problem (Ekvall, et al. 2001, Russel, et al. 2005). Ekvall and Tillman mention eight allocation procedures that they considered fair or reasonable based on the procedures' underlying perspectives (Ekvall, et al. 1997). More recently, in her review of allocation approaches, Curran concluded that no single method provides a general solution (Curran 2006). For LCA practitioners searching for an optimal procedure, learning these conclusions and finding multiple allocation procedures might prove

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[2] Examples of multifunctional processes requiring allocation include: incinerators, landfills, sawmills, dairies, oil refineries, metal smelting, transportation, etc. (Ekvall and Finnveden 2001).

[3] Heijungs and Frischknecht suggested that the allocation problem arises from the fact that when one models the unit processes used in the LCI assessment as a technology matrix, many times the matrix cannot be inverted and its pseudo-inverse does not yield an exact solution to the problem. From this perspective, which seems to apply only to descriptive closed-loop recycling cases where the technology matrix is square (i.e., the number of unit processes equals the number of balances), "…it is the database itself, the collection of process data that is used for finding the inventory table for any functional unit, that can create the allocation problem... independent of the case study at hand." (Heijungs and Frischknecht 1998)

frustrating. This could result in hasty selections of allocation approaches which, in turn, lead to incorrect or incomparable LCA results.

To deal with the allocation problem, ISO recommends the following stepwise procedure (ISO 1998, 2006b):

1. Avoid allocation when possible by (1) dividing the unit processes into sub-processes and gathering the required environmental burden data and/or (2) expanding the product system boundaries to include additional functions related to the co-products.
2. If allocation cannot be avoided, allocate the environmental burdens of each product based on their underlying physical relationships.
3. If allocation based on physical relationships cannot be done, allocate the environmental burdens of each product based on other relationships.

ISO provides additional recommendations for reuse and recycling scenarios primarily because more then one product system shares the burdens associated with extraction, processing and disposal and the inherent properties of materials may change (ISO 2006b). ISO recommends using a closed-loop allocation procedure for both "closed-loop product systems" and "open-loop product systems where no changes occur in the inherent properties of the recycled material" (ISO 2006b). For the latter scenario, they reason that recycling materials with constant inherent properties into another product system is equivalent to recycling it back into the original product system studied. Recycling displaces virgin material in both cases. Essentially, this assumption avoids expanding the system boundary by simplifying the allocation effect of recycling materials that do not change properties when recycled. If material properties change when recycled in an open loop, then ISO recommends using an open-loop allocation procedure. In general, it recommends that the allocation procedures use as a basis for allocation the following criteria in the following order: physical properties like mass, economic value, or the number of subsequent uses of the recycled material.

Sections 2.2.3.1.1-2.2.3.1.3 discuss the limitations and difficulties associated with each of the recommended ISO steps in light of the reviewed literature and consequential LCAs.

2.2.3.1.1 Problems with Avoiding Allocation by Subdivision or System Expansion

When sub-dividing multifunctional processes, Ekvall and Finnveden conclude that subdivision can help reduce, though rarely eliminate, allocation problems because these processes are not likely to consist of physically separate single-function sub-processes (Ekvall, et al. 2001). They further assert that only physically and economically independent sub-processes divide in such a way as to ensure the accuracy of information outputs when significant changes in production volume occur. In the case of open-loop recycling, they assert that subdivision will not reflect the consequences of any action very effectively in primary material production or final waste management, because they affect multiple products and any action affecting one function will affect others (Ekvall, et al. 2001).

In the case of system expansion, "…the boundaries of the system investigated are expanded to include the alternative production of exported functions"[4] (Ekvall, et al. 2001). Azapagic and Clift state "there are two essentially equivalent system expansion approaches," namely direct system enlargement and the avoided burdens approach (Azapagic, et al. 1999a). They either add or subtract the environmental burdens of alternative ways of producing the product or co-products to make them comparable as shown in the theoretical multi-output case in Figure 11.

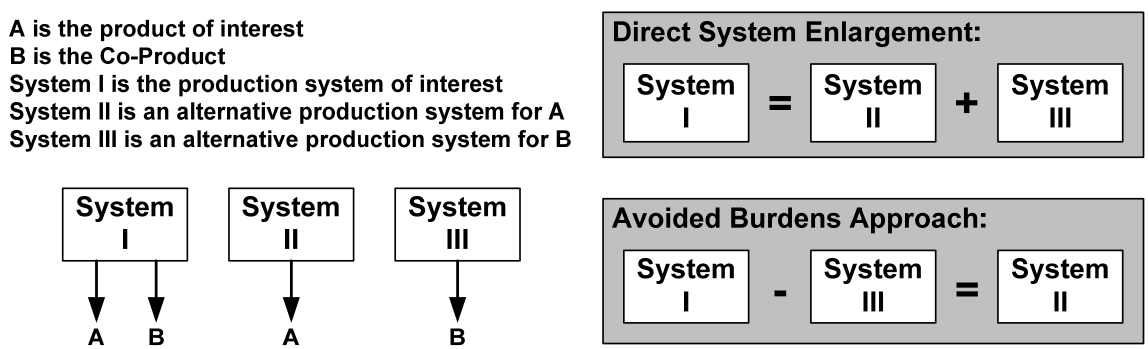

Figure 11: Two Different, Equivalent Ways to Expand Systems to Avoid Allocation

The problem with these system expansion approaches is that they rely on (a) the existence of alternative production systems and (b) reliable and accessible inventory data

[4] Exported functions refer to functions or co-products that are exported internally or externally of the product system studied.

for these production systems (Azapagic, et al. 1999a). If these two conditions could be commonly met in LCA studies, then the allocation problem could be avoided for a wide range of allocation problems via system expansion (Ekvall, et al. 2001). However, Ekvall and Finnveden suggest that one should undertake system expansion if the impact of the evaluated decision on indirect effects[5] is expected to significantly influence the LCA results. The problem is: *how can one know if the influence will be significant if one does not have the data?* To determine the significance of the effects one needs to learn if (1) the explored changes significantly affect the exported functions or co-products, (2) the exported functions or co-products significantly affected other external product systems and (3) the uncertainty on both the external product system inventory data and the effect from the exported function or co-product is not too large (Ekvall, et al. 2001). All of this seems to be reinforced by Curran who notes that while system expansion is the preferred approach to deal with allocation problems, because it avoids allocation altogether, it leads to a larger, more complicated model that requires more data (Curran 2006). This also seems to be the case with Weidema's proposed allocation procedure,

[5] Indirect effects refer to the effects that decisions in the product system of interest will have on other product systems.

which is based on identifying the determining co-product[6] for the multi-functional process in question, determining the level of utilization of the dependent co-products and determining their level of displacement of other products in order to establish an allocation of the burdens to each co-product (Weidema 2001).

In either case, whether trying to reduce or avoid the allocation problem through subdivision or system expansion, more data needs to be collected (if it exists, is reliable or is available) for relevant unit processes, which leads to more time, cost and potential data quality uncertainty.

2.2.3.1.2 Problems with Allocation Procedures based on Physical Causality

If the allocation problem remains after subdivision and/or system expansion, the allocation of the remaining environmental burdens should be carried out using causal, physical relationships. In the LCA community there seems to be general agreement on the guiding principles recommended by ISO, particularly referring to the principle that allocation should be based on the underlying causal physical relationships (Ekvall, et al. 1997, Azapagic, et al. 1999a, Finnveden 2000). Despite this general agreement however, Finnveden notes the example of chlorinated dioxins emitted from incinerators where two scientifically-based ways to establish causality (based on chlorine content of input

[6] The determining co-product is the product that has the single most influence regarding the inputs and outputs of the process. This influence may be due to the fact that it provides the most revenue, has a large market demand, is the only avenue of processing the co-product, etc.

materials/products or their heat value) could yield significantly different results (Finnveden 2000). Finnveden considers this an example of a knowledge gap that introduces uncertainty due to lack of scientific understanding of the process, although Azapagic and Clift consider this an example of material-related and process-related causalities (Azapagic, et al. 1999b). Regardless of viewpoint, some unit processes possess causal relationships that are not completely understood, and if a LCA practitioner wishes to use these relationships, he will likely need more information to make a more appropriate allocation.

2.2.3.1.3 Problems with Allocation Procedures based on Non-Causal Relationships

If the allocation problem remains after subdivision and/or system expansion and if causal, physical relationships have not been used to allocate the remaining internal functions, then non-causal relationships should be used. These relationships could be based on energy or exergy content, mass, volume, economic value, etc. (Ekvall, et al. 2001). Several reasons for using these relationships instead of causal relationships are: (1) lack of data or scientific knowledge, (2) convenience, the data is readily available or easier to get, and/or (3) the relationship may coincide with causal, physical relationships (e.g., when the ratio of outputs to inputs is fixed by stoichiometry (Azapagic, et al. 1999a)). Nevertheless, various researchers note that these relationships might "…not accurately reflect the effects of actions" (Ekvall, et al. 2001) and that they have generally been discredited for lack of justification (Weidema 2001). Despite these warnings from the LCA research community, non-causal relationships seems to be the predominant allocation method used in LCI practice (Ekvall, et al. 2001).

2.2.3.2 <u>Local Technical Uniqueness</u>

Extraction, production, distribution and end-of-life technologies used during a product's life cycle can vary with location. This local technical uniqueness affects the types and amounts of resources demanded and wastes produced by transformation of these resources. Environmental stressors associated with input resources change with employed technology; the burdens associated with electricity use, for instance, vary according to the mix of generation facilities supplying a region's grid. With regard to transformative processes, technology differences between regions, firms, facilities and even production lines within facilities can lead to order of magnitude differences in emissions (Finnveden 2000). Despite the dependence of physical flows on the particular processes and technologies utilized at different locations, some inventories rely upon generic process descriptions that differ with those used in practice (Ayres 1995). In this sense, local technical uniqueness is a specific type of data quality problem (See Section 2.6). Ignoring these differences reduces the accuracy of such inventories.

2.2.4 Limitations of Life Cycle Impact Assessment

Translating burdens into environmental impacts is, arguably, the most challenging of LCA's four phases. The main problems faced during life cycle impact assessment (LCIA) result from the need to connect the right burdens with the right impacts at the correct time and place. Therefore, this section addresses the problems associated with impact category selection, spatial variation, local uniqueness, environmental dynamics and decision time horizons.

2.2.4.1 Impact Category Selection

The mandatory elements for a LCIA involve the selection of impact categories, category indicators and models, the assignment of LCI results to the impact category (classification) and the calculation of category indicator results (characterization) (ISO 2000a). In this section, problems associated with all of these steps (except the characterization step) will be discussed in more detail as illustrated in

Figure 12.

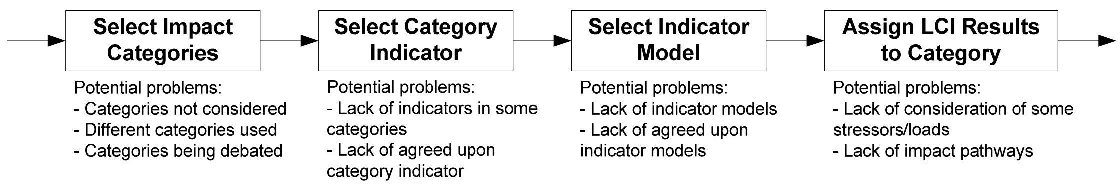

Figure 12: Potential Problems in Impact Category, Indicator and Model Selection

2.2.4.1.1 Current Difficulties with Selecting Impact Categories

Various practical difficulties currently impede impact category selection. These difficulties spring from a lack of current standardization in several impact categories present in the LCA literature, despite efforts to standardize them (Udo de Haes, et al. 2002). For instance, Finnveden noted that slightly different impact category lists have been proposed by different organizations (Finnveden 2000). These differences could be due to the impact modeling approach taken (midpoint versus endpoint) or the categories selected. The lack of standardization of some impact categories is also demonstrated by the recent debate as to whether certain impact categories such as soil salinity, desiccation and erosion should be independent categories or part of other, existing categories such as land use impact and freshwater depletion (Jolliet, et al. 2004). Similar discussions surround consideration of some impacts such as casualties due to accidents, with some suggesting the use of other tools in parallel (Jolliet, et al. 2004).

Disuse is one consequence of a lack of standardization in some impact categories. For instance, Finnveden observed that impact categories such as land use, habitat alteration, impacts on biodiversity, non-toxicological human impacts and impacts in work environment typically escape consideration (Finnveden 2000). This represents a potentially significant problem. As Hellweg and coauthors discovered, failing to consider chemical exposure at the workplace could lead to process optimizations at the expense of worker's health (Hellweg, et al. 2005). Obviously, other reasons besides a lack of standardization may cause LCA practitioners to not consider certain impacts such as: (1) lack of data to support a proper assessment of that category, (2) the belief that the category is not relevant in the given study and/or (3) lack of consideration of the category in the LCA methodology or tool used (e.g., if one used Eco-indicator 99). The first and last reasons are certainly sources of concern that need to be dealt with in order to improve the quality of LCA studies. Overall, these issues could create problems in the comparability of similar LCA studies, directly influencing the data gathering efforts and the quality of the results.

Selection of midpoint or endpoint (damage) impact categories potentially influences the confidence or relevance those involved in the decision process attribute to a LCA's results. For instance, endpoint categories are less comprehensive and have much higher levels of uncertainty than the better-defined midpoint categories (UNEP 2003). Midpoint categories on the other hand, are harder to interpret because they do not deal directly with an endpoint associated with an Area of Protection (AoP) as defined by

Udo de Haes and coauthors (Udo de Haes, et al. 2002) that may be more relevant for decision making, especially in policy (UNEP 2003).

2.2.4.1.2 Data Gaps with Toxicity-Related Impact Categories

Typically, certain impact categories such as land use, habitat alteration, impacts on biodiversity, human toxicity and eco-toxicity, aquatic eutrophication, and photo-oxidant formation suffer from significant data gaps (Finnveden 2000). The development of more complete databases may fill some of these data gaps, but impact categories such as human toxicity and eco-toxicity are not expected to be greatly improved due to the large numbers of chemicals used by society and the potential synergistic effects between these chemicals (Finnveden 2000). This concern is strengthened with statements from other researchers that say uncertainties "are likely to remain high, despite consensus building" (Pennington 2001) and from researchers that compared the aquatic ecotoxicity impact results of three different LCIA methods for various detergents and found different answers from the methods (Pant, et al. 2004).

2.2.4.1.3 Current Difficulties with Selecting Impact Category Indicators and Models

The previously noted problem of lack of standardization in the definition of impact categories is also seen when selecting an impact category indicator and model. In the case of some endpoint impact categories, such as damage to the abiotic natural environment (degrading of landscape, glaciers, waterfalls, etc.) and biotic natural resources (wild plants and animals used by humans), no indicator has been proposed (Jolliet, et al. 2004). In other categories, such as damage to the biotic natural environment (wild plants and animals, ecosystems) and abiotic natural resources (destruction or dissipation of non-renewable natural resources), damage indicators exist, but they have not been agreed upon (Jolliet, et al. 2004). In the latter category, more than one method is available for abiotic deposits (Finnveden 2000), which leads to different models. This can be significant because resource use is an important category for popular LCA methodologies such as the EPS system and Eco-indicator 99 (Finnveden 2005b).

2.2.4.1.4 Current Difficulties with Assigning LCI Results to Impact Categories (Classification)

In some cases, the effect of some inventory stressors or loads is not considered on potential midpoint or endpoint categories. One example is traffic noise that can affect human health. In this case, quantitative impact pathways to possible midpoints or human health damage have not been developed and LCI data for traffic noise is lacking (Jolliet, et al. 2004). A similar problem is associated with dispersal of invasive species due to anthropogenic processes where the challenge is to determine the circumstances under which it is a relevant damage category for the biotic natural environment (Jolliet, et al. 2004).

2.2.4.1.5 Potential Dangers of Using Pre-Defined LCIA Methodologies

On many occasions, a LCA practitioner may simply select a LCIA methodology provided as part of a LCA software tool. In these cases, the impact category, indicator and model selection and classification have been pre-selected for the user. This is appealing from the practitioner's point of view since it is faster and less costly. However, it must be noted and cautioned that depending on the methodology chosen and the impact categories of interest, the user may obtain qualitatively different results. For example, in a study comparing three LCIA methods, two midpoint-based approaches (EDIP97 and

CML2001) and one endpoint-based approach (Eco-Indicator 99) it was concluded that for the midpoint approaches, if the chemical impacts on human health and ecosystems are important, it matters which method should be chosen (Dreyer, et al. 2003). For EDIP97 and Eco-Indicator 99 it was speculated that, "…the two methods may produce diverging results, were they to be applied to comparisons of other types of products" (Dreyer, et al. 2003). Finally, some of these methods may not consider impact categories that are currently debated, which may be relevant to the LCA study being conducted.

2.2.4.2 Spatial Variation

During LCA's codification in the 1990s, researchers came to appreciate the importance of spatial considerations (Tolle 1996, Owens 1997, Graedel 1998b, Bare, et al. 1999, Hauschild, et al. 2000a). Emissions generated by a product's life cycle occur at many locations, enter multiple media (air, water, land) and cause impacts in relation to local environmental sensitivities (Owens 1997, Reap, et al. 2003). Unlike global impacts such as stratospheric ozone depletion and global warming, those affecting local, regional and continental scales require spatial information in order to accurately associate sources with receiving environments of variable sensitivity. Yet, most assessments continue to ignore spatial considerations despite a decade of awareness and method development meant to correct these problems (ISO 2000a, Potting, et al. 2006). The failure of spatially explicit methods to penetrate LCA practice suggests the need for continued efforts and motivates this portion of the review.

When discussing the limitations placed upon LCA by ignoring space, one usually uses the following classification scheme to describe different types of assessments (Potting, et al. 2006):

- *Site-generic* LCAs lack spatial information and assume globally homogeneous effects;
- *Site-dependent* LCAs use varying spatial resolutions for emission and deposition sites, and
- S*ite-specific* assessments model individual sources and local responses.

To better illuminate the connection between cause and effect, this review partitions the spatial problem differently. Instead of site-dependent and site-specific, this review discusses the problem in terms of spatial variation and local environmental uniqueness. Spatial variation refers to differences in geology, topography, land cover (both natural and anthropogenic) and meteorological conditions. Local environmental uniqueness refers to differences in the parameters describing a particular place (i.e., soil pH). This section discusses problems associated with spatial variation.

2.2.4.2.1 Spatial Variation and Transport Media

Site-generic LCAs become less accurate when spatially variable transport phenomena begin to dictate the fate of health and environmental stressors. Spatially explicit modeling using versions of the RAINS model (150 x 150 km grid squares) revealed that meteorological variations and local environmental sensitivities cause three order of magnitude acidification and eutrophication differences among European regions (Potting, et al. 1998, Huijbreghts, et al. 2001). Meteorological conditions and population distributions caused differences in health effects and damage to the “man-made environment” for different European countries when airborne pollutant emissions were modeled using the EcoSense model (50 x 50 km grid squares) (Kerwitt, et al. 2001). Later modeling efforts indicated that country-dependent acidification factors span a two order of magnitude range and that finer spatial resolution is needed (Hettelingh, et al. 2005).

Atmospheric variations are not the only spatial variations capable of influencing life cycle impact assessments. Topography and hydrology also play a part. Region specific impact score formulations for airborne deposition of eutrophying compounds contain factors for runoff, a factor strongly influenced by topography (Huijbreghts, et al. 2000). Estimates of water quantity impacts (i.e. drought stress on biomass, well failure, etc.) depend upon spatially explicit hydrology models or data sets (Reap, et al. 2004, Heuvelmans, et al. 2005). Groundwater contamination from landfills has been found to vary by as much as four orders of magnitude based on geological conditions and geographic location (Hellweg 2001).

2.2.4.2.2 Spatial Variation and Land Use

Changes in land use and land forms directly and indirectly affect LCAs. Some land use impacts fall within existing impact categories while others may require new categories (Udo de Haes 2006). Infrastructure supporting a product's life cycle (mines, farms, factories, road networks, landfills, etc.) occupies ecologically productive land, potentially leading to reductions in biodiversity, loss of biotic production and soil quality (Canals, et al. 2006). Land use indirectly affects assessments by changing meteorological and hydrological patterns. Land cover alterations lead to regional climate changes by effecting net radiation and the division of precipitation (i.e. runoff from impermeable surfaces) (Foley, et al. 2005). Precipitation division as well as diversion to agricultural, industrial and domestic consumption influence the hydrological cycle (Foley, et al. 2005).

"Land use impacts are highly dependent on the conditions where they occur…" (Canals, et al. 2006), and the spatial patterns of occupation influence ecosystem function (Turner, et al. 2001). In Lindeijer's review of land use impact methodologies, the "functional approach" to impact assessment contains land functions such as "erosion resistance" that partially vary with topography, for example (Lindeijer 2000). Even simple spatial variations in anthropogenic land forms, such as stack height, cause differences in estimated exposure efficiencies and health impacts (Nigge 2001a, Finnveden, et al. 2005a).

The spatial nature of both direct and indirect influences highlights the importance of explicitly modeling land use patterns. Indeed, those developing characterization factors for land use impacts recommend biogeographical region scale differentiation, at a minimum (Brentrup, et al. 2002, Canals, et al. 2006).

2.2.4.3 <u>Local Environmental Uniqueness</u>

The problem of space in LCA encompasses more than variations in geological, topographic and meteorological geometry. Each environment affected by resource extraction or pollution is, to a greater or lesser extent, unique. As a result, each local environment is uniquely sensitive to the stresses placed upon it by a particular product system's life cycle.

Evidence of environmental uniqueness' importance comes in the form of investigations of the influence of site-specific data and research programs directed at including local sensitivities in LCA. Ross and Evans found that simply disaggregating inventory data to allow site-specific estimates for photochemical smog clarified impact assessment (Ross, et al. 2002). Part of the previously mentioned multiple order of magnitude differences between acidification, eutrophication and health effect factors among European regions resulted from variations in local sensitivities (Potting, et al. 1998, Huijbreghts, et al. 2001, Kerwitt, et al. 2001). In the case of acidification, some of the difference almost certainly stemmed from the fact that soil buffering capacity varied across the analyzed regions. Human health can also prove locally unique in a particular impacted environment. For example, parameterizing urban landscapes by population density influenced estimates of air pollutant exposure efficiencies and revealed that generic assessments can underestimate the impacts of particulate emissions (Nigge 2001a, b). Population density proved a significant factor in determining impacts caused by vehicle and power plant emissions in other studies as well (Moriguchi, et al. 2000, Finnveden, et al. 2005a).

Modeling the geometry of extraction and pollution as discussed in Section 2.2.4.2 is an important step, but fully accounting for the problem of space in LCA requires attention to the parameters that further define unique, impacted areas. Identification and inclusion of these parameters and associated models represent an area of continuing research in LCA.

2.2.4.4 Dynamics of the Environment

"LCA is primarily a steady-state tool…" (Udo de Haes 2006) that typically excludes temporal information (ISO 2000a). Unfortunately, industrial and environmental dynamics affect impact assessment (Owens 1997, Graedel 1998b, Field, et al. 2001). ISO 14042 acknowledges that ignoring time reduces the "environmental relevance" of at least some results, but it does not discuss the inherent problems causing this reduction in relevance (ISO 2000a). This section highlights a number of the problems caused by ignoring system dynamics in life cycle assessment.

Temporal factors such as timing of emissions, rate of release, and time-dependent environmental processes affect the impact of pollution (Owens 1997). For example, a volatile organic compound (VOC) release timed to coincide with daylight hours produces more photooxidents than the same amount released at a constant rate during a 24 hour period (Graedel 1998b). Time-dependent environmental processes such as pollutant accumulation lead to threshold violations and accompanying variations in ecosystem impacts. Acidification impacts change when an ecosystem's nitrogen holding capacity is exceeded, for instance (Udo de Haes, et al. 2002). Other time-dependent processes require years of chronic pollution before manifestation occurs; decades of critical loading can be required before terrestrial eutrophication impacts appear (Udo de Haes, et al. 2002). Emissions generated by a life cycle under examination might synergistically interact with background pollution, leading to worse impacts that expected. Impacts such as aquatic eutrophication demonstrate seasonal variation in particular regions (Udo de Haes, et al. 2002).

In some cases, temporal patterns in product production, use and disposal also might influence the accuracy of life cycle assessments. Taking a fleet-centered approach to life cycle assessment, Field and coauthors theoretically demonstrated that transient environmental impact differences could dominate steady-state differences if one selected a short enough time horizon for evaluation (Field, et al. 2001).

Lacking dynamic representations or historical data, traditional life cycle assessment cannot account for environmental and industrial dynamics. Changes in pollution profiles as well as ecosystem responses are averaged, and impacts with sufficiently long delays may even be ignored. Responses to environmental interventions cannot be accurately modeled. Potentially important industrial transients receive no attention. Amelioration of these problems will undoubtedly improve LCA's environmental relevance.

2.2.4.5 Time Horizons

Time presents a problem for life cycle assessment apart from industrial and environmental system dynamics. LCA integrates environmental impacts over time. To obtain this integrated value, one must select an appropriate time horizon. Discussions about appropriate time horizons are not merely academic. A life cycle assessment of different incineration technologies found that the technology with the most favorable environmental profile changed with temporal system boundary (Hellweg 2001). Selecting integral limits and valuing impacts distributed in time are problems of continuing discussion in the LCA community.

With regard to integration, this discussion centers on the appropriateness of infinite vs. finite limits (Udo de Haes, et al. 1999). Infinite limits capture the entire effect of an impact, but such limits effectively discount short term impacts (Udo de Haes, et al. 2002). Furthermore, realistic integration over infinite time may prove challenging. While avoiding inaccuracies associated with extrapolating into the distant future, a finite limit effectively discounts long term impacts by truncating the period of consideration. One also faces the problem of selecting an appropriate finite limit, which might differ by impact category (Udo de Haes, et al. 1999). This limit could be chosen arbitrarily, or as Canals and coauthors suggest for land use, one might select the time required for a perturbed system to achieve a steady-state (Canals, et al. 2006). Of course, the latter limit assumes the existence of some method for determining the time to steady-state.

Valuation within the context of time horizon selection takes two forms. Implicit valuation occurs when one chooses to truncate impact consideration or allow infinite limits as previously mentioned. Explicit valuation occurs when one weights the value of an impact by time. In other words, explicit valuation occurs when one applies a discount rate to future impacts as one would discount future cash flows in a financial analysis (Udo de Haes, et al. 1999). Choosing an appropriate environmental impact discount or appreciation (the "discount" rate could be negative) rate is not a matter free of controversy.

2.2.5 Problems in Interpretation

The complexity of interpretation depends on whether the assessment objective, defined at the outset of LCA, is to target improvements ("what is bad"), to recommend a course of action (e.g., a strategy, prioritization of efforts, or choice of design), or to determine objectives for a more in-depth LCA. This section discusses interpretation from the perspective of the decision process. Aggregation is unavoidable when recommending one among a set of possible actions, and dealing with aggregation means dealing with the pernicious problems of weighting and valuation. Even if an assessment does not involve selection, one must still account for and manage uncertainty in the decision process. This section discusses problems in the interpretation phase stemming from weighting, valuation and uncertainty management.

2.2.5.1 Incorporating Subjective Values Using Weighting

Decision makers often consider multiple objectives that conflict or *trade off* across a set of decision options. To identify the most preferable decision option, one relatively weights the importance or value of different objectives and aggregates them into a single composite score. For LCA, this requires quantifying and comparing the value of different environmental impacts even when their units and scales differ. Numerous weighting methods with different preference elicitation processes have been proposed and applied to address this fundamental challenge. The type and amount of effort required by an elicitation process is proportional to the number of objectives, requirements for accuracy and rationality in preference structuring and number of stakeholders involved. Finnveden and coauthors conducted a comprehensive survey of these methods and evaluated them using a variety of performance criteria (Finnveden, et al. 2002). No weighting method met all of the authors' criteria; in fact, they theorized that none ever would (Finnveden, et al. 2002). The use of weights can pose a challenge for two general reasons:

1. It may be difficult to assure that an elicited weight accurately reflects a decision maker's value for some preformance objective, particularly with respect to other performance objectives.
2. Weights derived through different value (or preference) elicitation methods may not be comparable, and therefore, aggregation may not be possible without hiding added assumptions.

Particular instances of these problems are next discussed for the two broadest categories of valuation: monetization and all other methods.

Coming from environmental economics, monetization methods use a monetary measure to quantify value for all environmental impacts (Turner, et al. 1993). Most monetization methods measure willingness to pay (WTP). However, *who* is paying, *how* that is measured, and *what* values are actually involved may vary. Although the results of these different monetized measures share the same units, some authors warn that they should not be considered comparable or additive nor should they be combined with non-environmental costs (Bockstael, et al. 2000, Finnveden, et al. 2002). Numerous authors have discussed theoretical and empirical concerns with assigning economic value to environmental aspects (Kahneman, et al. 1992, Bockstael, et al. 2000, Farrow, et al. 2000). Some authors advocate less reliance on WTP in general, noting that they fail to account for regional differences and externalized costs (Matthews, et al. 2000) and that they use significantly different values than other human health valuation measures such as quality adjusted life years (QALY) (Hammitt 2002). Others contend that non-monetary forms of valuation provide a balance and must be considered (Ehrenfeld 1997). Determining a timescale for valuation is another major problem affecting monetization methods. To monetize future impacts, one must choose between discounting them (either through choice of a rate, or implicitly in willingness-to-pay methods) or simply ceasing to value them past a certain time (Finnveden, et al. 2002). When monetized impacts are aggregated, choices of discounting may be mixed and not transparent.

Decision analysis produced a variety of methods that achieve weighting. These techniques typically involve normalization to give different objectives (or metrics) compatible units, followed by weighting and aggregation of those normalized scores. Weighting methods rooted in decision analysis still suffer from bias and / or high information burdens. Weights or value functions constructed by direct preference elicitation suffer from behavioral (Weber, et al. 1993) or procedural bias (Mettier, et al. 2004) (Mettier, et al. 2006). Similarly, preferences elicited through indirect methods (i.e., revealed) may be of questionable relevance when transferred to the actual context of interest (Finnveden, et al. 2002). Bias also affects normalization, which can be used as a precursor to weighting (Heijungs, et al. 2006). Methods based on multi-attribute value (or utility) theory are currently believed to provide a rational axiomatic foundation for eliciting preferences for trade-offs (Keeney, et al. 1976). However, their elicitation processes require a large number of steps (Hertwich, et al. 2001). Assigning simple weights, on the other hand, may be less accurate, does not ensure rationality in applying preferences, and may suffer from anchoring biases (Mettier, et al. 2004). Similarly, distance-to-target weighting methods do not prescribe how to set targets, nor do they enforce equal importance for each objective, a requirement for inter-effect weighting (Finnveden, et al. 2002).

The preceding discussion on weighting focused on supporting selection between alternatives; however, ideally, weights could be used to assess whether, on a standalone basis, a product system is environmentally “good,” “bad” or even “sustainable.” Quantifying an absolute, aggregate measure in these terms is complicated by most of the previously presented weighting problems. Moreover, it depends on better definition of concepts of acceptable environmental performance and sustainability.

2.2.5.2 Uncertainty in the Decision Process

Whether the desired outcome of an LCA is a simple benchmark or a more involved recommendation of action, its reliability is influenced by variability and uncertainty. When confronting these topics, the ISO LCA series of standards briefly mentions uncertainty and sensitivity analysis, but the standards provide little guidance (ISO 2000a, 2000b, 2006b) as to when or how procedurally to apply them. *Uncertainty analysis* models uncertainties in the inputs to an LCA and propagates them to results. It can reveal whether there are significant differences between decision alternatives. S*ensitivity analysis* studies the effects of arbitrary changes in inputs on LCA outputs, which helps to identify the most influential LCA inputs. LCA researchers and practitioners have proposed or adopted different variations of these techniques (Björklund 2002, Lloyd, et al. 2007). Choosing one can be difficult, especially for predictive assessments, comparative assessments of complex systems or assessments with broad scope. Problems in uncertainty / variability analysis stemming from modeling uncertainty, using multiple uncertainties, analysis completeness and analysis cost compound this difficulty.

Modeling variability and uncertainty can be problematic. Probability distributions have been used in a variety of LCA uncertainty analysis methods (Huijbregts 1998, Björklund 2002, Ciroth, et al. 2004) and applied to numerous case studies (Maurice, et al. 2000, McCleese, et al. 2002, Geisler, et al. 2004). However, Björklund observes that few classical statistical analyses in the LCA literature describe their data sources or assumptions or reveal how probability distributions were determined (Björklund 2002). Some types of uncertainty, such as that due to LCA methodological choices, may not be representable using any uncertainty formalism and may need to be evaluated instead using sensitivity analysis (Björklund 2002, Lloyd, et al. 2007).

Problems also become apparent when one attempts to aggregate, for decision purposes, the influence that multiple heterogeneous uncertainty types have on LCA results. If probability distributions are unavailable as a result of data scarcity or use of non-probabilistic data, combination of multiple types of uncertainty representations might prove unavoidable. Unfortunately, combination of different uncertainty formalisms is often mathematically impossible and, when feasible, not theoretically sound, though this capability is being pursued by some researchers (Joslyn, et al. 2004).

Limitations in the comprehensiveness of an uncertainty analysis affect the quality of LCA conclusions and recommendations, and the cost of a comprehensive analysis, if possible, can be prohibitive. The degree to which comprehensiveness can be achieved (e.g., direct data collection, quantification of uncertainty in representativeness, model validation, etc.) varies across the phases of an LCA. For instance, developing models and characterizing uncertainty tends to be harder for impact assessment than for life cycle inventory (Owens 1997) and, likewise, harder for some indicator categories than others (ISO 2000a, 2006b). As a result, severe uncertainty and data limitations from difficult portions can dominate LCA outcomes and lead to inconclusive outcomes (ISO 2000b, Björklund 2002, ISO 2006b), or authors focusing on the readily quantified uncertainties may produce partial analyses that generate false confidence in the reliability of results (Bare, et al. 1999).

2.2.6 Data Quality – A Problem Affecting All LCA Phases

Having reviewed the challenges associated with making decisions under uncertainty, attention is next given to the main reasons for that uncertainty: data or models that are of poor quality. In her survey of approaches to improve reliability, Björklund generally identifies the main types of uncertainty due to data quality: badly measured data ("data inaccuracy"), data gaps, unrepresentative (proxy) data, model uncertainty, and uncertainty about LCA methodological choices (Björklund 2002). Specific instances of these data quality limitations are next discussed, grouped by those that are general, those that specifically affect life cycle inventory and those particular to impact assessment.

2.2.6.1 General Problems Limiting Data Quality

A number of general reasons explain the existence of poor or unavailable data. Data and models alike can fail to accurately represent the full spatial and temporal scope chosen in the initial phase of an LCA. Data can be effectively unobservable during the time period devoted to conducting an LCA. For example, consider product recovery infrastructure models and scenarios. Similarly, a LCA practitioner may not even recognize the need to collect some data. Uncertainty may also arise when different data sources measuring the same quantity conflict (Finnveden 2000, Björklund 2002). Standardized databases of LCA data are sought to reduce the burdens of data collection; yet, easily accessible, peer-reviewed data sets remain absent (UNEP 2003). There are few established, standardized or consistent ways to assess and maintain data quality (Vigon, et al. 1995). Regarding LCA databases, Bare and coauthors identify a fundamental conflict between the sophistication of the data and the variety of categories that the data covers (Bare, et al. 1999).

2.2.6.2 Data Quality in LCI

Some barriers to data collection are specific to inventory analysis. In general, the literature tends to agree that data for life cycle inventories is not widely available nor of high quality (Ayres 1995, Ehrenfeld 1997, Owens 1997). Data collection costs can be prohibitively large, e.g. when sub-metering must be implemented in an industrial facility, when data must be gathered from the field or when data must be frequently collected to remain relevant (Maurice, et al. 2000). In other cases, data exists outside of the LCA practitioner's organization, e.g., when withheld upstream or downstream by suppliers or other partners who have concerns (potentially valid) that sharing inventory data might reveal confidential information related to their competitive advantage (Ayres 1995). When available, external data can be of unknown quality. When data is not measured by the organization conducting the LCA, the accuracy, reliability, collection method and frequency of measurement may not be known and the limits of the data cannot necessarily be deduced (Lee, et al. 1995). As a result, uncertainty distributions or even upper and lower bounds are commonly unavailable (Owens 1997). Furthermore, mass balances are often not performed, or are performed incorrectly (Ayres 1995). Data also can become outdated, compiled at different times corresponding to different materials produced over broadly different time periods (Jensen, et al. 1997b). LCI data may be unrepresentative because it is taken from similar but not identical processes, is based on assumptions about technology levels, or uses averages, all of which may be features of database values (Björklund 2002). During inventory analysis data with gaps are sometimes ignored, assumed or estimated (Graedel 1998b, Lent 2003). Also, practitioners may extrapolate data based on limited data sets (Owens 1997). In fairness, it should be noted that ISO LCA standards require a company to document its data sources (ISO 2006a, 2006b), addressing many of the concerns raised in publications written in the late 1990s. Still, companies not complying with ISO might take these shortcuts, limiting data quality.

2.2.6.3 Data Quality in Impact Assessment

Probably the most serious data and model quality limitations affect the impact assessment stage, as there tend to be large discrepancies between a characterization model and the corresponding environmental mechanism (ISO 2000a, 2006b). The most fundamental barrier to model quality are limits to available scientific knowledge (ISO 2000a, 2006b). New chemicals constantly appear on the industrial market with poor models or measures of the mechanisms that disperse them into the environment. Finnveden points towards this being the case with dioxins (Finnveden 2000). Even if dispersion models exist, fate still may be ignored in calculations of impact (Bare, et al. 1999). Besides dispersion, the threshold levels that would create environmental damages may not be modeled or measured (Owens 1997) or may be represented using reduced order models, such as with linear dose-response curves (Bare, et al. 1999). Even if thresholds are known, they might not apply to any particular locale or time period, or they might be affected by synergistic combinations of chemicals (Bare, et al. 1999, Björklund 2002). To summarize the fundamental problem of modeling to an appropriate level of comprehensiveness, especially for environmental impact assessment, Bare and coauthors note that it is hard to know "where to draw the line between sound science and modeling assumptions" (Bare, et al. 1999).

2.3 Cracking Under Environmental Sustainability's Strain

Frosch and coauthors consider environmental metrics at the "heart of how industry defines environmental performance" and estimates "progress" (Frosch, et al.

1999). Metrics inform management, help monitor manufacturing and serve as goals in design problems. Unfortunately, current metrics fail in these capacities when the goal becomes one of achieving environmental sustainability, not simply monitoring continuous improvement. Reliance on post hoc analysis and the potential presence of environmental damage minimums in the possibility space for systems are the primary reasons for this failure, especially in the case of engineering design.

2.3.1 Post Hoc Analysis

Life cycle assessment generates inventories and impact assessments for product systems. One must have a product system or a sufficiently accurate model of a product system before estimating environmental impacts and associated metrics. In the case of original design, a product system is, by definition, unavailable, and system models often lack sufficient detail to serve as substitutes. In other words, LCA and associated methods are post hoc analysis tools incapable of providing the type of prescriptive guidance needed in design.

One might argue that after gathering the results of multiple LCAs for a number of product systems one could determine general trends which could serve as design guidelines. Continuous incremental improvements lead inexorably to environmental sustainability if one accepts this argument. However, the problems and limitations discussed in Section 2.2 coupled with the potential complexity of the environmental performance space in which the configuration of a product, process or system exist casts doubt on this outcome, as discussed in Section 2.2.5.2.

2.3.2 Local Minimums

Whether rooted in LCA or some other inductive tool employed by those engaged in EBDM, measures, metrics and indicators represent snapshots of an environmental system of interest. Unfortunately, partial representations frozen in time cannot fully capture a system's underlying dynamics. Snapshots clouded by the multiple problems and limitations discussed in Section 2.2 make LCA, EBDM's foundational method, especially unreliable. Such environmental representation limitations constrain the vision of those involved in decision processes to the near term. Constrained vision in the presence of an environmental performance design space containing local minimums seriously threatens one's ability to find sustainable design configurations, as the following discussion illustrates.

The range of potential, yet unrealized, product system states represents a design space. The search for an environmentally sustainable product system configuration represents the search for satisficing (Simon 2001) sets of design variables. Regardless of the algorithm selected to aid this search, a designer must remain cognizant of local minima. Consider the hypothetical environmental damage space presented in Figure 2. Designers manipulate design variables in an attempt to minimize the environmental impact of product systems. However, without understanding the underlying dynamics and mislead by inaccuracies in assessment methods, designers cannot accurately represent the design space; the square with thick black lines in Figure 2 represents the limits of prediction.

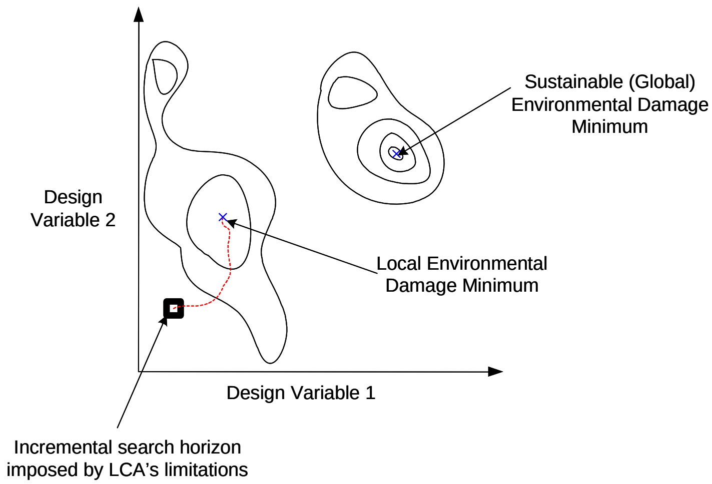

Figure 13: Potential Consequence of Using LCA to Aid Design in a Complex Environmental Space

The reader, benefiting from an omniscient perspective, can see the environmental damage contours, but designers can only see what falls within the bounds of the square. Four environmental damage minimums are apparent, but only one of the minimums is global. If one assumes for the moment that one can achieve sustainable operations by changing the two design variables to the coordinates of the global minimum, what is the likelihood of reaching the sustainable minimum through incremental improvement?

Given only snapshots of potential impacts or trends in estimated impacts, decisions executed at comparatively small time steps to decrease the unsustainability of a product system may lead to local eco-efficiency maximums or local environmental damage minimums which may fall short of sustainability, as the dotted line leading from the square to a local minimum in Figure 2 suggests. Damage allowed at these minimums surpasses the amount tolerated by the environmental system in this figure and may surpass tolerable levels in practice. Worse yet, having fallen into such a minimum, a designer lacking a comprehensive view of the design space or deprived of guiding design principles may believe that further improvements are not possible.

2.4 Summary and a Way Forward

As shown in Section 2.1, environmentally benign design and manufacturing (EBDM) grounds itself in life cycle assessment (LCA). The review presented in Section 2.2 reveals that LCA is a method replete with problems. As such, it appears less than capable of providing the sole foundation for engineering activities seeking to be *benign*. Section 2.3 removes any doubt about LCA's inadequacy by illustrating the process by which LCA guided EBDM could lead to less than environmentally sustainable outcomes. This section alluded to a radically different approach based on principles for sustainability. It is the development of this principled, biologically grounded approach that is the topic of Chapter 3.

CHAPTER 3: ABSTRACTION AND CONSTRUCTION OF HOLISTIC BIOMIMICRY

Chapter 3 documents the construction of the holistic form of biomimicry stated in the overarching hypothesis:

Biomimicry in the form of a governing set of living system principles can serve as a guiding framework for environmentally benign engineering.

Identification of biological principles contributing to the biosphere's inherent sustainability occurs during the first phase of construction. Translation of these biological principles into environmental sustainability guidance for EBDM dominates the second phase. Chapter 3 accomplishes these objectives by first setting appropriate study parameters, employing Constant Comparative Method to identify potential principles and finally constructing the bridge of reasoning that spans the gap between biology and engineering.

Qualitative validation occurs after principle identification and translation. Following principle extraction and statement in Sections 3.4 and 3.5, a panel of biology and bio-inspired design experts reviews the potential principles; the results of this review process appear in Section 3.6. Translation of the reviewed principles occurs in Section 3.7. Section 3.8 contains the second qualitative validation step. Translated principles and the guidance following from them are compared with the tenets of conventional EBDM and industrial ecology.

3.1 Constant Comparative Method

Constant Comparative Method (CCM) is an approach to generating theory from qualitative data (Strauss, et al. 1994). Glaser and Strauss originally developed the technique as an alternative to quantitative hypothesis testing and less formal qualitative theory generation techniques in the social sciences (Glaser, et al. 1967). Used primarily to extract unifying concepts from interview data, the method's originators contend that one can use it to analyze, "…any kind of qualitative information," including articles and books (Glaser, et al. 1967). Text passages, paragraphs and even entire articles serve as qualitative data points (Strauss, et al. 1998).

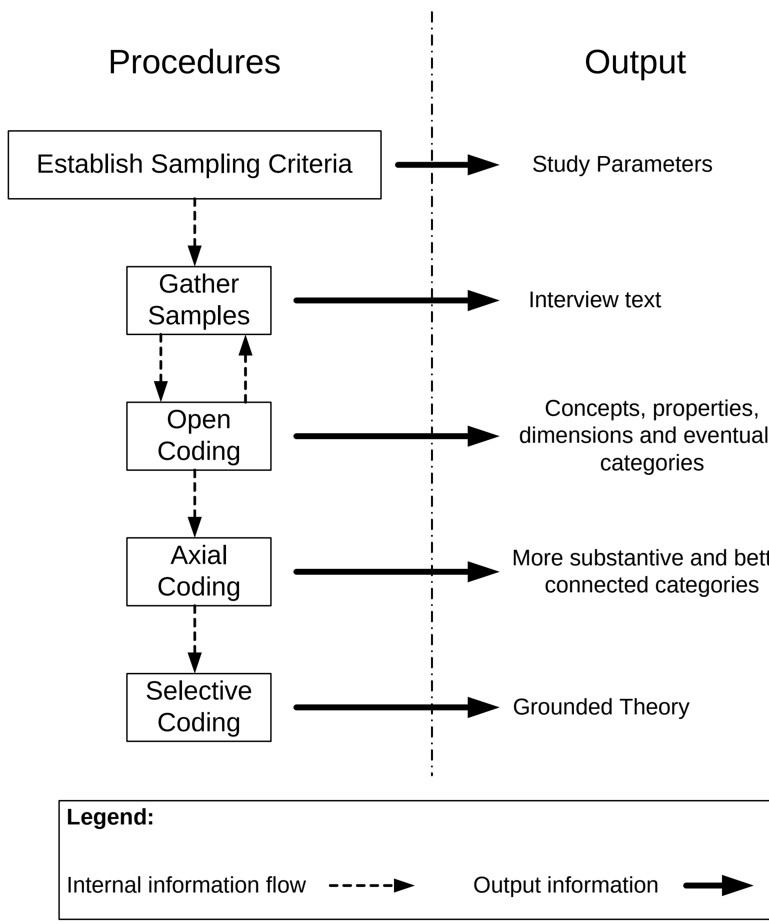

Figure 14: General Procedures and Basic Outputs for Constant Comparative Method [Based on (Strauss, et al. 1998)]

As Figure 14 reveals, procedures for coding and comparing passages form the core of the method. Coding refers to the process of grouping relevant passages under descriptive categories and of further organizing these categories into themes and abstract concepts (Auerbach, et al. 2003). Comparing refers to the constant process of reassessing and modifying categories as one adds new text to the data set. Comparison mandates iteration in the coding process. One uses multiple coding techniques, constant comparison and analytical skill to develop Grounded Theory (Auerbach, et al. 2003).

Only a portion of CCM finds application in this work because the aim is fundamental characteristics identification, not Grounded Theory construction. Consequently, Figure 15 emphasizes open coding, the iterative phase in which one identifies concepts, properties and dimensions. Axial coding and traditional literature surveys serve to develop categories established in open coding and eventually lead to the statement of principles. Sections 3.3 and 3.4 discuss coding, category formation and selection for development.

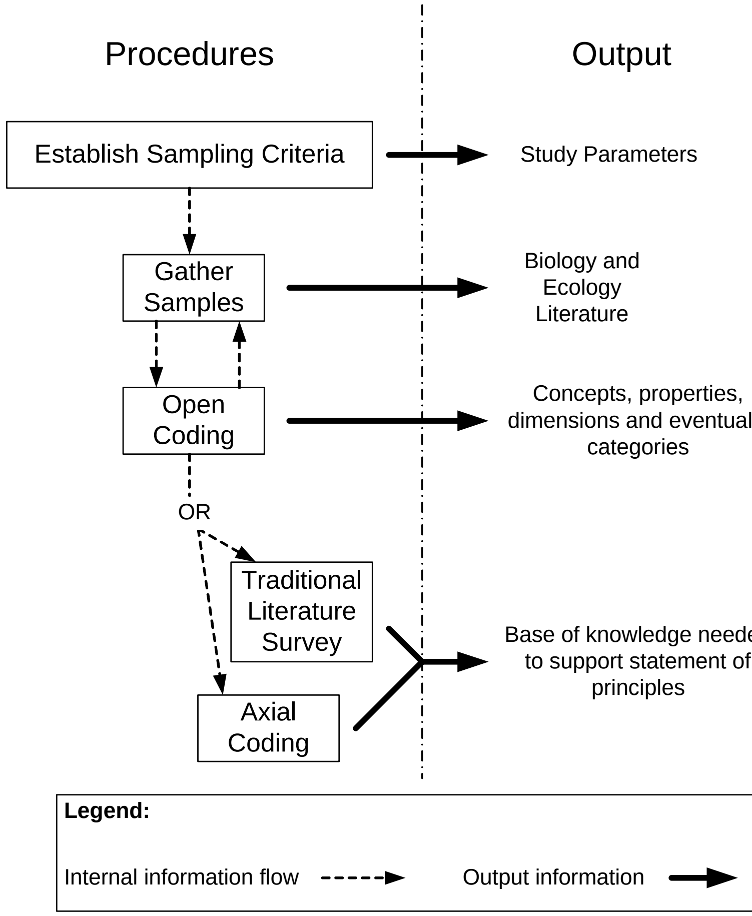

Figure 15: Modified Form of Constant Comparative Method Used in this Dissertation

3.2 Study Parameters

Studies using Constant Comparative Method or its elements require establishment of a few study parameters prior to employment of the method (Strauss, et al. 1998). Table 5 lists these parameters and briefly states the setting for each in this dissertation. Since literature serves as the foundation upon which biologically-inspired principles are built, Section 3.2.1 discusses its selection in greater detail.

Table 5: Study Parameters and Settings in this Dissertation

#	Study Parameter	Setting
1	Studied source material (i.e. site, group, etc.)	Biology and ecology literature
2	Data types	Book sections, journal papers and conference articles from academic works
3	Number of sites / observations	Arbitrarily set at ~100 sections, journals and articles
4	Study length	Time required to review the number of specified works
5	Foundational and motivational research questions	Research questions listed in Chapter 1

3.2.1 Literature Selection

Three criteria guided the selection of literature that serves as the foundation for this work. First, the selected literature needed to describe or explain the biosphere in accessible terms. Second, it needed to be general and encompassing. Finally, it needed to deal with the length, organizational and, to a lesser extent, time scales of interest in EBDM.

Excepting direct observation, biology and ecology literature provide the most credible information about the biosphere's composition and function. Therefore, general texts, respected journals and sections of journals focusing on these disciplines served as primary sources for this work. Biologically and ecologically specific journals included: *International Microbiology, Oikos, Ecology, Functional Ecology, Ecological Monographs*, etc. Issues and sections of *Science, Nature* and the *Proceedings of the National Academy of Science* (PNAS) dealing with biological and ecological topics contributed substantially to the analyzed literature base.

The generality requirement strongly influenced initial literature searches. Keywords such as principle, theory, rule and generalization were used to query databases such as Web of Science, JSTOR and Compendex. These keywords and their associated themes guided selection of articles from the previously mentioned journals as well as the bibliographies of papers identified during database searches. Literature reviews were also sought because they tend to concisely present the work underway in and beliefs held by sub-disciplines.

Engineering occurs on multiple scales. It is the premise of this dissertation that biological knowledge can inform environmentally benign engineering efforts on these scales. Therefore, the dissertation samples literature dealing with sub-cellular, cellular, organismic and ecosystem scales that also conforms to the generality requirement.

Selecting biology and ecology literature marks only the first step in Holistic Biomimicry's construction. The literature base must be systematically examined to find the unifying ideas which this dissertation seeks to uncover. The next section describes the procedure used to analyze the literature selected using the criteria in this section.

3.3 Coding in General

Understanding the means by which one identifies inherent characteristics requires an understanding of the coding process. Strauss and Corbin describe coding in detail (Strauss, et al. 1998). This section contains a brief description of basic coding concepts and the mechanics of generating and expanding categories. It begins by explaining concept identification and the conceptualization process. Then, it describes the use of properties and dimensions to increase the richness and explanatory power of categories.

According to Strauss and Corbin, each concept is a "labeled phenomenon," and conceptualizing is the act of labeling significant objects, events and interactions found in the data (Strauss, et al. 1998). One labels phenomena during open coding. Illustrative names or terms found in the data, in vivo codes, serve as labels for concepts. If one interviewed laborers in orchards, one would likely find concepts such as: apple, peach, produce, tree, picking, fatigue, etc. Similarities among concepts permit grouping / categorization; in practice, the label for one concept in a group becomes a category name. The produce concept in the orchard example encompasses more concrete concepts such as apple and peach. An interview transcript or article contains many objects, events and interactions. The identification of significant concepts requires the comparison of multiple data points and the application of the coder's intuition. The presence of multiple data points allows one to compare concepts extracted from each article or transcript. Concepts appearing frequently in datasets are considered significant. Many of the orchard concepts would likely appear in multiple interviews. With a small amount of imagination, a coder could combine these recurrent concepts under the category of harvest.

Having accumulated concepts and categorized them through comparison, attention turns to category development. An analyst develops a category by first identifying properties and dimensions during open coding and by connecting sub-categories during axial coding. Properties are category characteristics; dimensions establish the variation in the range of these characteristics. Returning to the orchard example, one might ascribe properties such as intensity, duration and productivity to the unifying concept / category labeled harvest. One further specifies the property of intensity by providing a dimensional range such as hurried to relaxed. The addition of properties and dimensions adds to one's knowledge of a concept / category and helps to further differentiate them. Even with one category, a few properties and some dimensional ranges, one begins to discern patterns for a harvest. One may even go as far as to hypothesize that different dimensional positions in harvest's space indicate the existence of sub-categories. For example, a hurried, short duration, yet high intensity harvest may typify the collection of a single crop on a large corporate farm ("factory farm harvest") while a more relaxed, longer duration, moderately productive harvest may indicate the collection of multiple crops on a smaller, family-owned farm ("family farm harvest"). In axial coding, one uses identified properties and dimensions and the data to better relate such sub-categories.

3.3.1 An Example of Coding in Sociology

To reinforce the reader's understanding of CCM's coding procedures, this section presents and explains excerpts from Straus and Corbin's text on qualitative research (Strauss, et al. 1998). Excerpts include interview transcripts as well as associated analysis.

When coding of a transcript commences, one may identify many concepts, or one might find a few concepts with associated properties and dimensions. Further coding and constant comparison allows one to group, expand and relate them. In the following excerpt representative of the early stages of open coding, the analyst identifies an important concept with accompanying dimensions and properties. The concept appears as an underlined text segment. The analyst closes his memo by orienting the data point provided by the interviewee in the conceptual space defined by the identified properties and dimensions.

PROPERTIES AND DIMENSIONS OF THE PAIN EXPERIENCE

Interview Quote: *The pain in my hands from my arthritis is really bad in damp cold weather. I wake up with it in the morning, and it lasts throughout the day.*

The only time it seems to get better is at night when I am warm in bed and under the covers.

Memo – Open Coding: This woman is describing her "pain experience." We can see that the pain has, among others, the properties of intensity, location, and duration. Another property is degree of relief. When she says that it is "really bad," she is giving us a dimension of the property of intensity. The location of the pain is in her hands, and it is of "long" duration, lasting throughout the day. Relief is possible under conditions of warmth.

Taking off from this code note, I can hypothesize that pain can vary in intensity from severe to mild, that it can be located anywhere in the body an in more than one place, and that it can last a short or a long time. Also with this type of pain and for some persons, it is possible to obtain relief under certain conditions, so that pain relief can vary from possible to impossible. There is also a property of variation; that is the intensity of the pain can vary, depending on location in the body, degree of activity, time of day, and weather. Finally there is the property of continuity of the pain. It can be continuous, intermittent, or temporary. In this case, one might say it is intermittent.

Memos help the coder analyze the qualitative data, establish relationships and begin the process of categorization into unifying concepts. The following memo illustrates part of this process for the previously cited excerpt. By questioning the potential influence of the cause of pain on the "pain experience," the analyst tests the generality of this concept. The analyst begins to learn whether "pain experience" is sufficiently encompassing to form a separate category.

Memo – Theoretical Note: QUESTIONS ABOUT PAIN

What are some of the causes of pain besides arthritis? There are many different causes of pain, for example, cancer, injury, surgery, tooth decay, amputation , and childbirth. How is pain experienced in each of these? Is it expected or not expected… Is some pain more intense than other pain? Does the intensity vary over time? Take childbirth or cancer, for instance; is it more intense early or later in the course… From here, I might want to sample the pain of childbirth, that associated with advanced or dying cancer patients, pain in children, and pain in the elderly to see if these make any difference.

In this final excerpt, the analyst develops the emerging category of "pain experience" by identifying more properties and dimensions. Some basic relationships between properties also emerge. For instance, pain type and intensity are related when the pain of a pulled muscle is mentioned.

Memo – Theoretical Note: OTHER POSSIBLE PROPERTIES AND DIMENSIONS OF PAIN

Arthritis is certainly not the only cause of pain. One can also have pain from an injury, say a pulled muscle or a mild burn. Using my own experience with each of these, what else can I learn about pain? Well, pulled muscles or mild burns are usually the result of injuries, which makes them temporary in nature rather than permanent. How might I describe the pain of either? Pain from a pulled muscle

> is usually intensified when I try to move whatever body part is affected. This happens with arthritis also. This gives me another condition for intensification of pain.
>
> Under conditions of movement, pain can increase. What about the mild burn? This is different. Pain of a burn can be described as kind of a continuous burning sensation that eventually fades. This points to still another property, that is, type of pain. Pain varies in type from burning to throbbing, acute, or whatever…

3.3.2 An Example of Coding Physical Science Literature

Coding text found in the physical sciences literature differs from coding interview excerpts. Comparisons largely deal with physical, as opposed to social, phenomena. Authors attempt to explicitly state the ideas that one labels as concepts when applying CCM. Since the ideas have been explicitly stated, most concepts take the form of in vivo codes. One may also promote many of these concepts to categories and sub-categories because authors tend to use terms common to a discipline or sub-discipline. To highlight the ways in which these differences affect the coding process, this section presents sections of code memos used to identify and develop the biological principles discussed in the remainder of this chapter. APPENDIX A contains the complete set of code memos used in this work.

The first code memo excerpt analyzes a few paragraphs in a paper by Vermeij (Vermeij 2006) that contributed significantly to the development of one biologically inspired principle. The cited passage contains the essence of the analyzed paragraphs and is presented to help connect the analysis to the original document. As one can see, the primary effort in coding prepared text resides in capturing the essential concepts communicated by the author.

> "…physical and economic principles of emergence, competition, feedback and evolution governing historical change are timeless. Beneath the details of time and place, there are repeated structures and patterns in history."

Four words jump from the page: principles, governing, repeated and patterns. He is clearly stating that there are "principles" that do not merely influence but "govern" historical change. These governing principles lead to "repeated structures and patterns." Now, this is quite powerful stuff. For him, history is billions of years, and over these eons, he is saying that the same sorts of things (patterns and structures) recurred because of these principles.

He names these principles, and it should be noted that two of these definitively depend upon the existence of life, while the other two are, to my knowledge, often associated with life. Are these principles considered the standard ones for biology? Would I be able to open a biology textbook, turn to the first chapter and see definitions of "emergence, competition, feedback and evolution"? Evolution will be there, but what about the others?

When I think of principles, I think of "first principles from engineering" - conservation of mass, Newton's Laws, the laws of thermodynamics, etc. But, are

Vermeij's principles like engineering principles? Can I perform emergence calculations; is there a first law of competition?

Potential concepts: governing principles, emergence, competition, feedback, evolution, functional types

The second excerpt comes from a memo that codes a paper by Lotka (Lotka 1922a). It represents a more advanced stage of coding. The existence of unifying concepts / categories allowed the identification of properties and dimensions as well as concepts. Though, perhaps, not immediately evident, the memo from which this excerpt hails contributed to the development of the same principle as the previous memo. Comparisons of just these two excerpts reveal that both Vermeij and Lotka wrestle with the fundamental physical and biological bounds placed on life over evolutionary time. Vermeij considers a number of broad principles while Lotka focuses on mass and energy constraints. Their reasoning combines to generate a rather surprising conclusion, but this is the topic of later sections.

"…the fundamental object of contention in the life-struggle…is available energy. …in the struggle for existence, the advantage must go to…organisms whose energy-capturing devices are most efficient at directing available energy into channels favorable to the preservation of the species."

The author's opening lines contain two concepts, <u>life-struggle</u> and <u>available energy</u>, that he discusses for the remainder of the paper. Life-struggle is almost certainly synonymous with evolution, though a case may be made for the concept of natural selection. Available energy seems to have the properties of availability and utilization. Both of these properties emerge when taking the perspective of the biosphere or "organic world," as Lotka labels it. Available energy's availability seems to have dimensions ranging from abundant to scarce while utilization ranges from full to unutilized.

He contemplates the relationship between natural selection and available energy and formulates a hypothesis about this relationship in the first few paragraphs. He hypothesizes that natural selection works to maximize "energy flux through the system" by preserving and increasing organisms that capture energy efficiently. This hypothesis introduces the concept of energy capture with the property of efficiency and dimensions between efficient and inefficient. So, using the concepts, properties and dimensions presented thus far, Lotka hypothesizes that natural selection in the presence of abundant available energy guides the biosphere toward higher utilization by selecting efficient energy capturing organisms.

Potential Concepts: evolution, natural selection, available energy (P: availability D: abundant to scarce; P: utilization D: full to unutilized), energy capture (P: efficiency D: efficient to inefficient)

3.4 Principal Extraction of Principles

Drawing an analogy with vinification, coding academic literature in biology and ecology is akin to stomping grapes. Just as stomping frees the juice from each grape coding liberates fundamental ideas from the confines of each publication. Liberation is not sufficient for winemaking or identification of fundamental characteristics, though. One must also gather and concentrate the desired products. This section describes the comparison and categorization of biological concepts identified in ~100 code memos. It concentrates the more diffuse information present in the code memos into potential biological principles.

During coding, concept repetition or the appearance of multiple concepts centered on a related theme suggests the existence of a category. Figure 16 plots the frequency of different concepts appearing in the code memos. APPENDIX A contains a master list of the concepts, properties and dimensions found in each code memo.

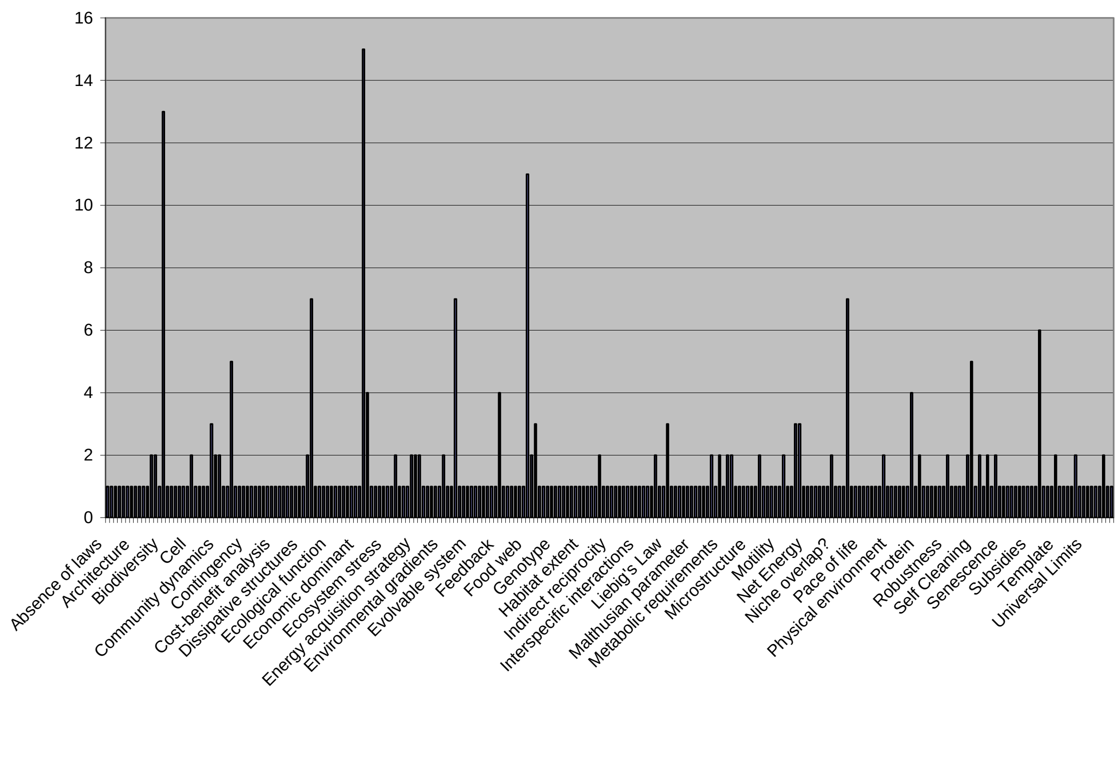

Figure 16: Frequency of Concepts Encountered during Coding of Biology and Ecology Literature

The coding process identified many concepts in the sampled biology literature, but few recur with great frequency. Concepts in Figure 17 recur with greater frequency than most and each concept appears in ~4% or more of the sampled literature. Of these, some concepts, such as ecosystem, evolution and selection, describe hopelessly expansive biological ideas.

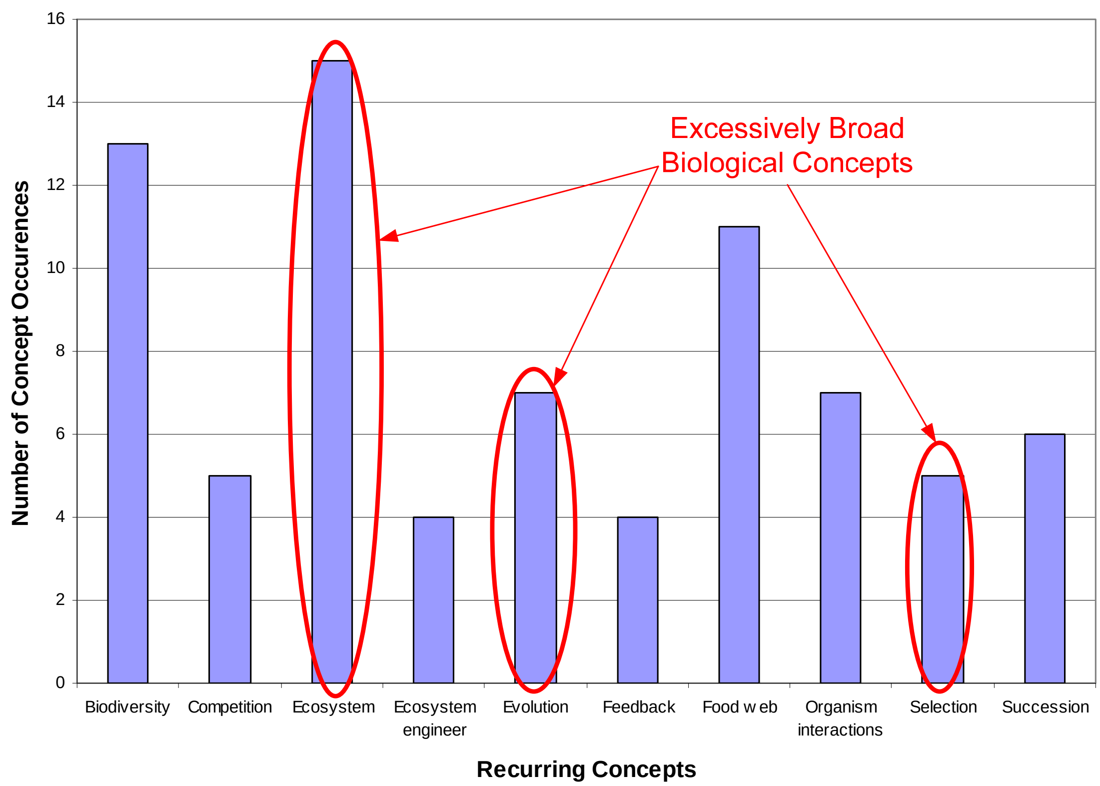

Figure 17: Frequency of Recurring Concepts

A number of other concepts label similar phenomena yet occur less frequently. Eliminating the ineffectually broad and grouping the related, one generates categories of prevalent biological concepts found in the sampled literature (

Table 6).

Table 6: Categories

Initial Categories	Number of References	Number of Related Concept Occurrences	% of References
Biodiversity	21	21	22.6%
Competition	5	7	5.4%
Ecosystem Engineers	5	5	5.4%
Feedback	6	6	6.5%
Interaction Web	18	25	19.4%
Metabolic Limits	6	8	6.5%
Micro / nano structure influenced adhesion	4	11	4.3%
Mutualism and Cooperation	9	10	9.7%
Organism Interactions	9	7	9.7%
Succession	8	8	8.7%

Each category in

Table 6 contains related concepts, properties and dimensions identified during open coding. Each category label represents a wealth of ideas to the coder that may not be apparent to the reader. To reduce the knowledge gap, Table 7 contains a brief description of each. The listed categories also represent rich sources of biological inspiration for EBDM; further development of all ten requires an unreasonable amount of effort for one dissertation. Therefore, Table 7 divides them into those pursued and those left for future work. The following six criteria were used to select categories for further development.

1. Strong presence in the sampled biology and ecology literature
2. Foundational importance in biology and ecology
3. Potential for new and innovative ideas based on:
    a. Lack of consideration outside of biology and ecology
    b. Insufficient biological grounding of past efforts
4. Ease of study

5. Correspondence with existing ideas in EBDM

6. Influence on different length or organizational scales

Specific reasons supporting the pursuit decision appear alongside each category's description (See Table 7).

Table 7: Category Descriptions and Reasons For / Against Further Development

	Category	Description	Reasons For / Against Further Development
Pursued	Biodiversity	Biodiversity encompasses the way in which organisms differ as well as the relationships between organism diversity and ecosystem properties. Some primary types of biodiversity include: taxonomic, genetic, functional and trophic. Biodiversity influences ecosystem properties such as productivity, robustness and resilience. Recognition of ecosystem-diversity relationships appears responsible for propelling biodiversity to the fore in modern biology.	• Appears as a concept in a large fraction (22.6%) of sampled literature • Strongly influences ecosystem properties important for maintenance of the biosphere
	Ecosystem Engineers	Ecosystem engineering entered the biological lexicon during the final decade of the 20th century. The term refers to the changes organisms make in their habitats not directly related to trophic flows. Ecosystem engineering creates, maintains and alters habitat; some modifications affect many square kilometers and continue to generate effects for millions of years. The spatial and temporal extent of these changes makes ecosystem engineering a powerful force influencing organism evolution.	• Recent appearance of this biological idea means it has had little time to influence other fields of science or engineering • Studies habitat changes in some ways analogous to engineering activities, and therefore explores a topic important in EBDM
	Interaction Webs	Organisms, groups of organisms, communities and ecosystems are bound in a web of interaction. Such webs include the trophic concept of food webs as well as less developed concepts such as mutualist and control webs. This category deals with the fundamental transfers of energy, material and information among organisms.	• Food webs and related ideas recognized as important areas of study in industrial ecology • Previous applications of these ideas in engineering limited • Applicable at facility length scales

Table 7 continued

	Metabolic Limits	Metabolism usually refers to the sum of the internal chemical process required to maintain an organism's life, and it includes the energy required by these processes. The metabolic limits category focuses on the energetic aspects of metabolism, especially at the organism scale. Given the fundamental importance of metabolic activity for life, it is not surprising that such a category appeared in the sampled literature.	• Fundamentally important in biology • Historically, received less treatment in industrial ecology than other bio-inspired ideas (Lifset 2004). • Operational at the organism length scale
	Micro / Nano-Structure Influenced Adhesion	The adhesion at micro and nano length scales category is an example of a grouping that covers small scale biological phenomena. It contains concepts describing common biological characteristics responsible for reducing and increasing adhesion. Concepts dealing with these behaviors and their benefits also appear in the coded literature.	• Past work in EBDM suggests ideas related to this category lead to significant environmental benefits • Operational at sub-product length scales
	Succession	Succession is the largely directional change in community structure and processes with time (Odum 1987). Where other categories focus on individual organism interactions or webs of existing interactions, the succession category deals with the development of interactions over time.	• (See Interaction Webs)
Future Work	Competition	At its core, competition is the striving for a thing between two or more actors. Organisms compete for food, mating opportunities, territories, predator refuges and other resources in the environment. Competition occurs within species and between species. Biology recognizes it as a major force shaping life on Earth; some even see it as the paramount force driving the evolutionary trajectory of organisms (Vermeij 2004).	• Extensive study by biologists and, most importantly, economists, engineers and others beyond the life sciences reduces likelihood of finding innovative applications.
Future Work	Feedback	Feedback refers to the classic notion of information returned to a "controller" as well as the process of controlling, though control may not be centralized or top-down. In the biosphere, feedback takes many forms, operates on multiple time scales and appears in a myriad of places. Chemical, radiant, acoustic and other signals carry information relevant to organisms, and systems display both top-down and bottom-up control. Signaling and resultant control occurs from small fractions of a second to far longer spans of time. Feedbacks occur in cells and organisms to maintain vital processes (i.e. homeostasis in mammals). Feedbacks occur in ecosystems, constraining or promoting an organism or process. Indeed, it is difficult to find a living process not producing or partially	• Extensively studied in engineering (i.e. controls, cybernetics) • Difficult to separate the influence of feedback from other concepts in biology

		governed by feedback.	
	Table 7 continued		
	Mutualism and Cooperation	Mutualism and cooperation refer to organism behaviors that benefit both parties. The category deals with these behaviors, the types of systems they engender and the conditions under which they arise.	• Extensively studied beyond the bounds of biology; therefore, the likelihood of finding innovative ideas is reduced
	Organism Interactions	Organism interactions encompass the entire sweet of possible engagements between two or more organisms ranging from predation to mating. It technically includes other discussed categories. However, it is somewhat limited in that its concepts focus on describing specific behaviors without exploring the conditions required for or ramifications of these behaviors.	• Difficult to separate the influence of individual interactions from responses of systems such as food webs • Investigated as part of other categories

3.5 Biological Principles: Key to the Biosphere's Sustainability

In this section, one finds statements and explanations of the principles extracted from biology literature using the techniques presented in the previous sections.

3.5.1 Biodiversity

Scientific study of life's diversity began, at the latest, with Darwin's "Origin of Species"(Darwin 1859, 1936). Where Darwin's work centered on species generation, many recent efforts focus on understanding the relationship between diversity and ecosystem functions. Ecosystem functions influenced by biodiversity include: goods and services provision, productivity, stability and efficient resource utilization. In fact, maintenance and improvement of these functions appears to depend on the maintenance of biodiversity.

The positive correlation between biodiversity and ecosystem functionality generally holds across scales and habitats. Forms of biodiversity enhance ecological functions on multiple spatial scales. On the microscopic scale, bacterial cultures exhibit greater functionality as species richness increases (Bell, et al. 2005). Plant species diversity enhances ecosystem functions at larger (m^2) scales as well (Kirwan, et al. 2007). At least some diversity-functionality relationships hold across different time scales. Studies conducted by Bell, Kirwan and coworkers lasted no more than two years, but Kiessling found that species diversity correlated with ecosystem stability across million-year time scales when studying reef fossil records (Bell, et al. 2005, Kiessling 2005, Kirwan, et al. 2007). Kirwan studied terrestrial plant communities while Kiessling analyzed marine data; both found positive correlations between biodiversity and ecosystem functions (Kiessling 2005, Kirwan, et al. 2007). These results indicate that the diversity-functionality relationship applies in markedly different habitats. Correlation between diversity and ecosystem functionality on multiple spatial and temporal scales as well as its continuity across habitats argues strongly for its consideration as a general biological principle. With only a few cited studies, doubt remains, though. The presented examples may represent special cases.

Data gathered by biologists and ecologists in the last decade and a half indicates the commonality of biodiversity's relationship with ecosystem functionality. Multiple studies and reviews find that genetic or species diversity influences the functionality of terrestrial and marine ecosystems (Hooper, et al. 2005, Kahmen, et al. 2005, Kiessling 2005, Crutsinger, et al. 2006, Tilman, et al. 2006, Worm, et al. 2006, Kirwan, et al. 2007, Maherali, et al. 2007). Biodiversity increases productivity (Bell, et al. 2005, Worm, et al. 2006, Kirwan, et al. 2007, Maherali, et al. 2007). It enhances ecosystem stability (Hooper, et al. 2005, Kiessling 2005, Tilman, et al. 2006, Worm, et al. 2006). It even appears capable of improving material resource efficiency (Hooper, et al. 2005).

Researchers documented the appearance of these functional influences in the short (Bell, et al. 2005, Kahmen, et al. 2005, Kirwan, et al. 2007), medium (Tilman, et al. 2006) and long term (Kiessling 2005). They detected biodiversity's power at spatial scales ranging from petri dishes (Bell, et al. 2005) to the globe (Kiessling 2005). Clearly, the preponderance of data supports the generality of biodiversity's positive correlation with ecosystem functionality.

Despite the individual imperative of evolution, interacting organisms achieve greater degrees of functionality when viewed as a whole (ecosystem). Furthermore, greater organism diversity generally enhances functionality, to a point. The preponderance of data gathered to date supports the existence and generality of this trend which one may summarize as:

Life maintains and enhances ecosystem functionality by maintaining and enhancing biodiversity.

Life's use of diversity for stable and efficient production should hold special interest for those hoping to achieve environmentally sustainable production in engineering.

3.5.2 Ecosystem Engineers

Jones and coauthors first defined ecosystem engineers as, "…organisms that directly or indirectly modulate the availability of resources to other species, by causing physical state changes in biotic or abiotic materials" (Jones, et al. 1994). Though not labeled as such, work noting the importance of ecosystem engineering appears as early as the mid to late 19th Century (Buchmann, et al. 2007). Darwin's famous work describing the influence of earthworms on soil serves as an example (Darwin 1881). Jones and company introduced the ecosystem engineering concept to draw attention to non-trophic interactions that affect species (Jones, et al. 1994). Physical state changes caused by ecosystem engineers influence consumable energy and material resources (light, nutrients, water, etc.), nonconsumable resources (living space, predator free zones), abiotic constraints (temperature, salinity, wind, etc.) and information exchange (sound attenuation, light quality, temperature, etc.) (Jones, et al. 2007). In essence, organisms possess the capacity to impact their habitats and the habitats of others in potentially profound ways through other than trophic means.

Ecosystem engineers hail from multiple kingdoms, occur in many habitats and span length scales from macro to micro. On the macroscopic end of the length scale, Balsam fir trees (*Abies balsamea*), a member of Kingdom Plantae, engineer forest environments (Hastings, et al. 2007). In Kingdom Animalia, one finds Humpback whales creating bubble nets at sea and stingrays digging pits in intertidal zones (Hastings, et al. 2007). Earthworms engineer soil habitats (Lavelle, et al. 2007). At the microscopic end of the length scale, marine and freshwater phytoplankton, members of Kingdom Protista, modulate light availability (Jones, et al. 1994). These kingdom, habitat and scale spanning examples clearly illustrate the scope of ecosystem engineering. But, are ecosystem engineers common?

Jones and company listed 29 individual species and groups of organisms when introducing the concept of ecosystem engineering, and Hastings and coauthors site more than 18 species when exploring the spatial and temporal ranges of engineering effects (Jones, et al. 1994, Hastings, et al. 2007). Some cited groups such as "forest trees" and “higher plants” cover large swaths of life’s tree and Earth’s surface. Biologists’ opinions of the concept also point to its prevalence in the natural world. Laland observes that, “…all organisms modify their environments…” through ecosystem engineering, and “…such modifications can have profound effects on…the control of energy and material flow…” (Laland, et al. 1999). In fact, some authors point to the ubiquity of ecosystem engineers and ecosystem engineering when questioning the value of the term, if not the concept (Reichmann, et al. 2002). The existence of numerous ecosystem engineers and the encompassing nature of the concept’s interpretation by the community of biologists prove its commonality.

Having stated the basic concept and argued for its generality and commonality in the biosphere, the way to principle statement stands open. The biological principle embodied in the ecosystem engineering concept is simply the essence of its original definition.

Ecosystem engineers impact their environments through physical changes of state.

Not unlike the inventions of man, nature’s evolutionary inventions impact the environment via changes of physical state. Study of the types and magnitudes of these changes may illuminate the impacts potentially produced by proposed acts of human engineering.

3.5.3 Webs of Life

Darwin's Origin of Species famously closes with a description of an imaginary "tangled bank" of organisms (Darwin 1936). While his great contribution to biology focused on the organisms inhabiting the bank, it is important to note that their "tangle" of interactions earns a place amongst his final remarks. His parting words imply that material, energy and information connections among species play an important role in the biosphere.

His word choice suggests a chaotic, knotted and somewhat unsatisfactory arrangement of interactions, but quite to the contrary, the "tangle's" nonrandom architecture decisively affects the functions and properties of life's many webs. In the last four decades, researchers taking theoretical, experimental and empirical approaches to food and mutualist web analysis identified multiple network structures, constraints and other characteristics (May 1972, Warren 1990, Pimm, et al. 1991, de Ruiter, et al. 1995, Bascompte, et al. 2007, Okuyama, et al. 2008). The outcomes of these analyses sometimes differed. For instance, Watts made the connection between diversity and population stability in an ecosystem one of his environmental principles, but May's purely mathematical analysis found the complexity introduced by diversity a potential source of instability (May 1972, Watt 1973). Later empirical work gave new life to the link between diversity and stability in terms of resilience (Okuyama, et al. 2008). Despite these and other differences in interpretation, all authors tended to find structures and patterns in ecological networks.

These structures and patterns decisively contribute to the emergence of network functions and properties. Energy distribution and material cycling through trophic flows have long been known to be important functions of ecological networks (Lindeman 1942, Patten 1985), and network architecture influences them (Fath 2007). Properties of food and mutualist webs such as dynamic stability (resilience to perturbations in species population sizes) and static stability (robustness to species loss) depend critically upon network topology and the strength of network forming links (May 1972, Pimm 1984, de Ruiter, et al. 1995, Jordano, et al. 2003, Rooney, et al. 2006, Bascompte, et al. 2007, Okuyama, et al. 2008). Here again, researchers disagreed about the types of architectures conferring or hindering stability. Authors conducting theoretical studies tended to conclude that weak links between a few sparsely connected species conferred network stability (May 1972, Pimm 1984). Later authors attribute stability to asymmetries in "fast" and "slow" energy channels in food webs (Rooney, et al. 2006) and to asymmetries in visitation frequencies in mutualist webs (Bascompte, et al. 2006). Most recently, one empirical study even concluded that strong symmetric connections enhanced dynamic stability (Okuyama, et al. 2008). Regardless of the position taken, these and other authors share the conviction that network topology and link characteristics strongly influence observed network properties.

Turning one's focus to findings held in common by various researchers, one observes that those exploring Darwin's tangle share two conclusions:

1. Ecological networks possess unique structures that clearly deviate from random assemblages.
2. Ecological network topology and link characteristics, network architecture, strongly influence overall network functions and properties such as cycling and stability.

One might fairly ask whether the previous two conclusions apply to most ecological network types or whether these conclusions only represent a minority of the communities in each type. In other words, one might ask whether these conclusions are general and common. Examination of review papers and the samples used in specific studies can shed light on the generality and commonality of these conclusions. Pimm and coauthors' review states, "…that food webs from a wide range of terrestrial, freshwater, and marine communities share a remarkable list of patterns…" (Pimm, et al. 1991). Rooney and company utilized food web data from multiple terrestrial and aquatic ecosystems to ground their ideas about energy channel asymmetry (Rooney, et al. 2006). Jordano's study of mutualist networks used community data from tropical forest, temperate forest, scrubland, mountain and arctic habitats found on at least five continents (Jordano, et al. 2003). Even researchers modeling ecological networks using purely theoretical approaches identified patterns (May 1972, Pimm 1980, Jorgensen, et al. 2006). Whether using ecological data or theoretical models, ecologists commonly see general patterns in ecological networks.

Species organized into material, energy and information networks with nonrandom topographies and particular linkage strengths over the course of evolutionary time. Living within solar energy constraints, these networks came to effectively use Earth's material resources while resisting system collapse through exploitation or internal instability. These structures and their associated node and link parameters promote material cycling within dynamically stable networks robust to node loss. One can encapsulate ecological network knowledge with the broad statement:

Life distributes and retains resources using nonrandom network architectures.

As mankind learns to live sustainably between Sol and Terra, patterns of network organization selected and tested by the planet's other inhabitants offer valuable insights for humanity's systems designers.

3.5.4 A Metabolic Limit

Early in the Twentieth Century, Lotka proposed that a subtle relationship between energy and living systems exists. He stated that evolution generates and selects living systems that maximize total energy flow per unit time subject to constraints (Lotka 1922a). Controversially, he even suggested that energetically driven natural selection constituted a fourth law of thermodynamics (Lotka 1922b).

Focusing upon the former part of Lotka's proposition, the maximization of total energy flow per unit time, later authors developed the controversial "maximum power principle" (Hall 1995, Odum 1995, Hall 2004). Odum's formulation of the maximum power principle states that physical as well as biological systems which maximize "power intake, energy transformation…production and efficiency" develop and prevail (Odum 1995). This principle figured prominently in the development of his embodied energy analysis concept known as emergy analysis (Odum 1995). Others have, in turn, borrowed, modified and merged Odum's emergy techniques with exergy analysis (Hau, et al. 2004).

However, the extensive body of work only briefly highlighted in the previous paragraph grew from the first portion of Lotka's statement. The second, in contrast, received little direct attention during the past century. The latter portion of Lotka's proposition, his concept of energy consumption *constraints*, serves as the historical root of an argument for the existence of biological energy limits. Development of this argument begins with exploration of the influence of energy flows within the context of evolution.

Recent work in evolutionary biology suggests that physical, especially thermodynamic, principles played an important role in guiding the evolution of organisms (Vermeij 2006). Vermeij sought to determine the "nature and scope" of contingency within the context of evolutionary innovation by investigating claims of uniqueness in the fossil record (Vermeij 2006). Contingency, in this context, refers to the evolutionary advantage afforded to organisms demonstrating plasticity (adaptability) in the face of stochastic events such as mass extinctions. It also refers to the evolutionary legacy of past stochastic events. Organisms surviving a particular random event were selected for those traits which allowed them to adapt to the new situation. He defines evolutionary innovations as new features of or conditions created by organisms which allow new or improved functional performance (Vermeij 2006). He wished to learn the extent to which random precedent, on one hand, and physical principles and economic selection, on the other, dictated the appearance of innovations. If claims of unique evolutionary innovation proved plausible, contingency would be shown to dominate the evolution of living systems. If, instead, innovations recurred, physical and economical principles would be shown to play an important role in guiding their development. Vermeij's examination of the fossil record and related literature lead him to the conclusion that, "…important ecological, functional and directional aspects of the history of life are replicable and predictable" (Vermeij 2006).

To help explain the observed predictability, Vermeij turned to a thermodynamically rooted concept articulated by Chaisson (Chaisson 2001, Vermeij 2006):

> *Whenever suitable energy flow is present, selection from among many energy-based choices rewards and nurtures those systems that engender pathways capable of drawing and using more power per unit mass up to a point beyond which too much power can destroy a system.*

In other words, living systems attempt to harvest energy at the maximum possible rate while minimizing the amount of mass, the biological equipment, needed to accomplish this task. However, selection also eliminates adaptations which draw dangerous levels of energy per unit mass. This concept bares an uncanny similarity to the one advanced by Lotka roughly eight decades earlier, though Chaisson takes cosmology as his starting point and grounds his ideas in non-equilibrium thermodynamics (Chaisson 2001). The ideas of Lotka and Chaisson and the evidence presented by Vermeij suggest the existence of a guiding principle or, at least, a concise summary of observed behavior for living systems related to energy consumption. Acting over time, this principle would tend to leave the living world populated with "power" dense systems that conform to certain limits on the rate of energy consumption per unit mass. While "maximum power" may be difficult to specify, a limit on "power per unit mass" should be readily detectable. The question arises whether such a limit on energy consumption per unit mass indeed exists in nature.

Evidence supporting the existence of a limit on energy consumption per unit mass for organisms recently came to light. An examination of organisms ranging from the smallest bacteria to the largest mammals found evidence of universal specific (per unit mass) metabolic rate limits (Makarieva, et al. 2005b). Biologists define "metabolism" as the collection of an organism's biochemical processes (Arms, et al. 1987, Campbell 1996). "Metabolic rate" is energy consumption or use of food through cellular respiration per unit time (Arms, et al. 1987, Campbell 1996). Specific metabolic rate is, therefore, the rate of energy consumption per unit mass.

For organisms spanning 20 orders of magnitude in body mass, Makarieva and coauthors determined specific metabolic rates, performed statistical analyses and concluded that, "a universal optimum favoured by natural selection in diverse taxa," may exist (Makarieva, et al. 2005b). They found that a majority of the specific metabolic rates determined through observation and literature survey fell between 1 and 10 W/kg (Makarieva, et al. 2005b, a). Expanding the range to 0.1-10 W/kg captures a larger portion of their observations (See Figure 18).

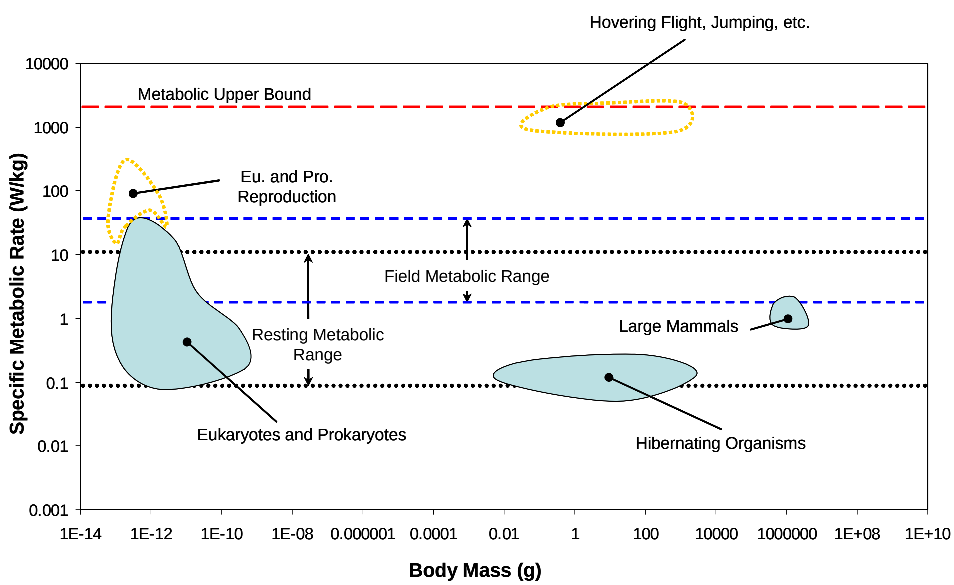

Figure 18: Specific Metabolic Rates and Ranges for Selected Organisms [Adapted from (Makarieva, et al. 2005b, a)**]**

It is important to note that most of the data in Figure 18 represents basal and standard metabolic rates. Basal and standard metabolic rates measure energy consumption per unit time for resting, unstressed endotherms (warm-blooded organisms) and ectotherms (for cold-blooded organisms), respectively (Campbell 1996). These data largely fall within the resting metabolic range diagramed in Figure 18. The field metabolic range is more representative of the 2 to 40 W/kg metabolic limits observed for organisms in less restful, more stressful natural habitats (Makarieva, et al. 2005a). Excursions beyond these limits occur, but they are confined to temporary, intense activities such as cellular reproduction and hovering flight. It appears that:

Life accepts a limit on mass specific metabolic rate.

Identifying "universal" metabolic rate limits appears tantamount to detecting the limits to energy consumption rates first conceived by Lotka. The fact that the same limits apply to all known organisms spanning 20 orders of magnitude in body mass seems consistent with Vermeij's ideas concerning physical principles that temper the contingency of evolution (Vermeij 2006). This leads one to contemplate whether such biological bounds should also play a role in tempering technical development.

3.5.5 Rough and Clean

Biology researchers identified the relationship between hydrophobic micro/nano-structured surfaces and particle adhesion within the last decade (Barthlott, et al. 1997), though others connected surface roughness and water repellency much earlier (Wenzel 1936, Cassie, et al. 1944). They observed that hydrophobic micro/nano-structured plant leaf surfaces remained clean in contaminant rich environments (Barthlott, et al. 1997).

The presence of small scale roughness reduces particle adhesion while increasing water repellency which allows highly mobile water droplets to clean plant leaf surfaces. They dubbed this self-cleaning phenomenon the "Lotus-Effect" in honor of the plant famous for exhibiting it (Barthlott, et al. 2001). Studies of gecko feet revealed that micro and nano-structures were responsible for their adhesive properties and that those hydrophobic structures could clean themselves with or without water (Autumn, et al. 2006). The same features that allow a gecko to adhere to almost any surface also resist contamination and self-clean.

The lotus and the gecko are markedly different organisms. They are taxonomically distant, belonging to different kingdoms when using the traditional classification. The former floats in position while the latter is highly mobile. They bare different trophic classifications – autotrophe for the lotus versus heterotrophe for the gecko. Despite these foundational distinctions they both approach the problem of adhesion control in a similar manner. Development of the same surface features to achieve the same ends in different organisms found in different taxa is an example of convergent evolution. It may even suggest the work of general forces. As Vermeij states when discussing repeated evolutionary innovations, "…the principles of physics and economics imply that many derived functional states are achieved many times in many clades because they impart substantial widely applicable advantages to their bearers" (Vermeij 2006). If evolution of hydrophobic micro/nano-structures represents a general response to fundamental physical and economic forces, then one expects to find multiple examples of their deployment.

Adhesion modulation through the use of hydrophobic micro/nano-structures is not confined to a handful of organisms. Rather, it occurs in multiple organisms spanning more than one kingdom. Over 180 plant species possess hydrophobic leaves with small scale structuring (Neinhuis, et al. 1997). Insects utilize self-cleaning surfaces (Wagner, et al. 1996b). As mentioned, geckos use hydrophobic micro/nano-structures to adhere, prevent adhesion and self-clean (Hansen, et al. 2005). Even higher organisms such as whales employ nanorough skin features to maintain cleanliness (Baum, et al. 2002a). Whether resisting adhesion or adhering, many organisms rely upon hydrophobic micro/nano-structures to accomplish the task.

It appears that the responses of multiple organisms to the soiling trials and travails of life on Earth converge. Organisms turn to hydrophobic micro/nano-structures to control adhesion and gain the upper hand on surface contamination. The following statement summarizes the extracted biological principle.

Life modulates adhesion using hydrophobic micro and nano scale structures.

The prevalence and success of life's approach to soiling and adhesion recommends it for application in a technological context.

3.5.6 Succession

Ecological succession is the term for the gradual changes in population sizes and organism composition in a community (Parker 1994). Study of these changes, especially in plant communities, took root early in the formation of modern ecology. By the end of the 20th Century's first decade, Cowles confidently describes succession in terms of "vegetational cycles" proceeding from a vigorous "period of youth" to one of "old age" that approaches an "equilibrium" (Cowles 1911). Clements presented the first theory of succession which notably viewed it as an autogenic (organism driven) developmental process proceeding toward a climax (Clements 1916). Gleason challenged many of the concepts in Clements synthesis (Gleason 1927). He initiated an alternate line of thought about community changes that emphasized individual species over communities and randomness over determinism. But, near the end of the 20th Century, Odum would describe Clement's succession as development process thesis as, "…one of the most important unifying theories in ecology" (Odum 1987). Today's ecologists merge revised versions of the ideas initiated by Clements and Gleason. They regard succession as a directional though stochastic process strongly influenced by climate, topography, disturbance regimes and other factors. This view recognizes that the biosphere's constant state of flux and stochasticity may prevent convergence on a climax ecosystem, allow multiple types of climax systems despite similar conditions and even destabilize climax communities.

Ecologists view succession as a general process influencing communities, "…at a broad range of scales from the microscopic to the continental, from minutes to millennia" (McCook 1994). Observations of terrestrial communities, especially dune plant communities, inspired the first work on succession (Barbour, et al. 1999, Johnson, et al. 2007). Succession occurs in benthic marine communities involving many organisms from kingdoms besides Plantae (Denitto, et al. 2007). It influences community change where land and water meet to form wetlands, proving especially important in the development of peatlands (Batzer, et al. 2006). Phytoplankton communities experience succession, thus illustrating this ecological concept's importance at microscopic scales

(Reynolds 2006). From land to sea and forest to phytoplankton, succession is a global phenomenon touching a broad range of organisms. But, is this process common and influential or merely sometimes apparent in a few select ecosystems scattered across the biosphere?

As one expects of a concept given a prominent place in ecology, succession appears in many of the major terrestrial, freshwater and marine biomes. One observes predictable succession patterns in boreal and deciduous forests (Archambault, et al. 1997, McDonald, et al. 2007). Krakatau archipelago, site of multiple volcanic eruptions since 1883, bore witness to multiple, directional assemblies of communities of tropical flora and fauna (Whittaker, et al. 2007). It is not limited to areas prone to forest ecosystem climaxes. Development toward grassy ecosystems also occurs, and some propose using this tendency for the purposes of conservation and restoration (Stadler, et al. 2007). Succession influences the development of ecosystems in harsh terrestrial environments as well. A study of desert plant community development on debris flows in the Grand Canyon noted plant assemblages similar to those in the surrounding biome (Bowers, et al. 1997). More importantly, this study noted successional characteristics such as a transition from short-lived pioneer plants to long-lived varieties and autogenic soil development. Even in the high arctic where abiotic factors often dominate one finds directional changes in flora characteristic of terrestrial ecological succession (Mori, et al. 2007). It transpires in transitional areas between land and sea such as wetlands, marshes and coastal areas (Batzer, et al. 2006, Denitto, et al. 2007). Successional changes in streams have been documented (Miyake, et al. 2003). Ecologists even consider the ecosystems of entire seas as undergoing multi-millennia succession (Bonsdorff 2006).

From land to sea, succession is clearly commonplace, and while the biotic component is not always dominant, it is often influential.

Ecological succession is both generally applicable and commonly observed in nature. Communities across the globe progress from pioneer to mature stages of development. Measurable changes in ecosystem energetics, nutrient cycles and community structure accompany shifts in a community's population sizes and composition during succession (Odum 1987). Odum assembled a list of parameters that quantify the maturation process (Odum 1969). Others developed metrics that quantify ecosystem maturity based on extent and organization of material or energy exchanges (Ulanowicz 1996a, Ulanowicz, et al. 1997). These syntheses and the examples cited in previous paragraphs suggest that one may summarize a principle for succession as follows.

Ecosystems tend toward greater interaction specialization, energy storage, trophic efficiency, recycling structure and organism life span.

Complex climax ecosystems embody or show progression toward the characteristics listed in the previous statement. Given their persistence, their sustainability, those developing technical systems at comparable organizational scales may find something worth emulating in evolution's design.

3.6 Biological Review

Misinterpretation of research is a concern when the individual reviewing the research in question hails from a different field. This work relies upon an established method for extracting themes from qualitative data to guard against such errors. As a further check and a form of validation, the work also utilizes a panel of biology and ecology experts to critique the biologically inspired sustainability principles abstracted in the previous section (See Table 8).

Table 8: Biology review panel members

Expert	Domain	Institution
Dayna Baumeister, Ph.D.	Biology, Biomimetics	Biomimicry Guild
Steven Vogel, Ph.D.	Biology	Duke University
Marc Weissburg, Ph.D.	Biology, Ecology	Georgia Institute of Technology

This section describes procedures and tools used to accomplish this objective. It also relates the critique for each principle along with its implications for validation. Specifically, this section describes the T-Square web tool used to facilitate the critique and documents the outcome of the review. It serves as one of the first steps in the dissertation's validation.

3.6.1 Review Procedure and Tools

The review procedure consisted of four steps. Each review panel member was asked to:

1. Read a description of the principle extraction procedure similar to the one found in Sections 3.2-3.4
2. Review the statement and description for each principle
3. Answer three questions concerning the principle's validity
    a. Are the presented principles and supporting essays reasonable interpretations of the biological and / or ecological facts and theories? If not, why not, and what is missing?

b. Are the presented principles and essays excessively biased toward one prevailing interpretation of the biological and / or ecological facts?

c. In light of your answers to the previous two questions, would you consider the principles to be generally valid biological statements? What caveats and qualifications are needed or would improve the statements?

4. Respond to the comments of fellow reviewers when appropriate

One should note that the structure of panel members' responses took an unexpected form. In formulating their reviews, they avoided the structure offered by the three questions in Step 3. They instead tended to write short essays that generally communicated their thoughts about the biological appropriateness of each principle. As a result, the commentaries presented in Sections 3.6.2-3.6.7 represent an effort by the author to recast the reviewers' general statements in the more precise form of the original three questions from Step 3. Complete copies of each reviewer's comments appear in APPENDIX C.

A webpage with forum and thread capability facilitated the review process. All necessary text and data were posted to forums on a webpage using the Georgia Institute of Technology's T-Square web portal. Each panel member entered his or her critique as a thread in the appropriate forum. Screen shots of the interface appear in APPENDIX C.

3.6.2 Commentary on the Biodiversity Principle

Reading the critiques, the reviewers found the biodiversity principle and essay an unbiased and a reasonable, though vague, interpretation of the biology and ecology literature. However, some imprecisely defined elements of the essay prevented them from endorsing its general validity. All three expressed concern with the imprecise notion of ecosystem functionality. They expressed a desire to see links between biodiversity and specific ecosystem functions before endorsing the principle's general validity.

3.6.3 Commentary on the Ecosystem Engineers Principle

All three reviewers made comments suggesting that they found the principle and supporting essay reasonable, unbiased and generally valid interpretations of the biology literature. However, comments by two of the reviewers suggest that applying the principle may prove difficult. Vogel noted that the ubiquity of impacts caused by organisms might mean that, "the term may not be a useful one." Weissburg similarly observes that one must define functional roles for each potential ecosystem engineer, and he implies that the roles taken may vary considerably with the organism. These comments suggest that one might find it difficult to easily define classes of functional roles.

3.6.4 Commentary on the Web of Life Principle

The panelists found this principle and essay a reasonable and unbiased interpretation of the literature. Speaking of ecological networks, Vogel states that, "…they may look messy, but that reflects complexity rather than randomness." Weissburg concurs that, "…biological networks contain properties of interest…that may be generalizable." Both of these comments are clearly in line with the statement of biological principle in this section. Baumeister sees the potential for multiple principles related to the existence of interconnected biological networks in the essay. Such a position lends support to the reasonableness of the interpretation, but represents a problem for the sought declaration of general validity.

Baumeister's position is a kind of positive dissent against the general validity of the principle on the grounds that it is not fully refined. She accepts the importance of this line of thought and believes principles can spring from it, but she would seem more comfortable with a statement that includes a specific network property found in living systems. However, the other reviewers appear less concerned with achieving this level of specificity. So, it is reasonable to say that the majority of the panel supports the general validity of this biological principle.

3.6.5 Commentary on the Metabolic Principle

From a strictly biological perspective, all three reviewers found the principle and essay a reasonable, unbiased and generally valid statement of the supporting biology. While their thoughts on the reasons for and potential implications of a metabolic principle differed, none of them questioned the existence of a limit recognized by organisms.

3.6.6 Commentary on the Micro/Nano Surface Principle

The reviewers agree with the principle and supporting essay. All three find it reasonable, unbiased and generally valid. The use of an argument based on convergent evolution proved particularly persuasive. Searching for examples of convergent evolution in order to identify important characteristics at the organism and sub-organism scale may be a valuable tool for bio-inspired design.

3.6.7 Commentary on the Succession Principle

Older ecological writings unduly influence the succession based principle. The presence of the bias toward older references leads the three panelists to make statements questioning the biological reasonableness of this principle. They consequently doubt its general validity. However, some also make statements suggesting that related ideas might be salvaged by focusing on work produced in the last decade.

3.6.8 Review Summary

Of the six potential biological principles selected for future development, review panelists found four reasonable, unbiased and generally valid statements of biological knowledge. A fifth, biodiversity, proved reasonable and unbiased but too vague for immediate acceptance as generally valid. Only the succession based principle failed the biology review. This potential principle apparently fell victim to a literature sample populated by older references containing discredited ideas.

3.7 Biologically Inspired Guidelines for Sustainable Engineering

Here, the biological principles for sustainability are restated and translated into biologically inspired guidance for sustainable engineering. In addition to general guidelines, each translation discusses means of quantifying each guideline and lists associated measures, metrics and indicators potentially applicable to analysis or design.

3.7.1 Industrial Diversity

Statement of a guideline based on the biodiversity principle presented in Section 3.5.1 appears straightforward. Maintenance and enhancement of many properties important for long term survival of organisms and ecosystems hinge on maintenance and enhancement of biodiversity. Loosely speaking, an imperative to increase industrial diversity emerges from contemplation of biodiversity's importance in the living world. But, what is industrial diversity?

Translating the biodiversity principle into an engineering guideline requires thoughtful classification of independent organizational entities. Classifications by genetic strain, taxonomy, functional group and trophic level exist in the living sciences, and each plays a part in defining biodiversity. One needs the context supplied by equivalent industrial classifications to give meaning to guidance derived from the biodiversity principle. Industrial ecology typically considers individual companies as the basic unit of analysis (Ayres 1994). This approach to classification comes with an economic taxonomy of North American Industry Classification System (NAICS) codes, and it is not difficult to establish analogs to functional and trophic groupings. Extractive industries sit near the bottom of the industrial food chain with refiners, manufacturers and commercial providers occupying progressively higher levels. The canonical approach also firmly places the scale of influence at the multi-entity level. Taking industrial ecology's approach to entity classification, the diversity guideline becomes:

Maintain and enhance industrial network functionality by maintaining and enhancing economic diversity.

Having established a unit for diversity measurement, one can readily apply a number of biodiversity measures and metrics found in biological literature. The simplest measure of biodiversity is species number, also known as richness (Purvis, et al. 2000). One may also use other levels of biology's hierarchical classification scheme such as genius, family, order, etc. (See Figure 19).

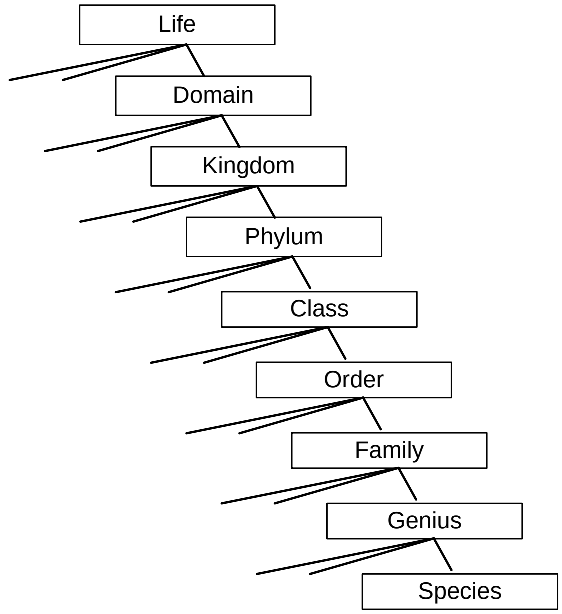

Figure 19: Biological Classification of Organisms

As mentioned, NAICS codes can serve as one industrial analog to life's taxonomic tree. Counting these codes at a specified level in an industrial habitat such as an industrial park, region or even national economy provides a measure of industrial diversity. Biologists also use diversity indices (Legendre, et al. 1998, Kahmen, et al. 2005, Tilman, et al. 2006). The Shannon-Wiener Index (H_1) and concentration (H_2) are two common, dimensionless indices (Legendre, et al. 1998).

$$H_1 = -\sum_{i=1}^{q} p_i \log(p_i) \tag{1}$$

$$H_2 = -\log \sum_{i=1}^{q} p_i^2 \tag{2}$$

In the previous two equations, q stands for the total number of species in a habitat, and p_i refers to the proportion of the i-th species. Based on Shannon's entropy relations, the first achieves its minimum (H_1=0) for one species, and one finds a maximum when q species are evenly distributed in the sampled habitat. Concentration is the probability of consecutively drawing two of the same species from a sample. It assumes that the number of organisms in a sample is large enough to approximate non-replacement probabilities with proporitions (p_i). Simply replacing species with NAICS codes allows one to calculate the same indices for industrial diversity.

Functional biodiversity is another form of natural diversity. Organisms in the same functional groups share an ecologically significant trait. Such traits might include leaf nitrogen content, phosphorous uptake, filtering / recycling activity or primary production (Petchey, et al. 2002, Bell 2007). Biologists estimate functional diversity by counting the number of functional groups identified in a studied habitat. Sorting individual businesses by industrial function (ore extraction, smelting, machining, etc.) leads to a similar industrial measure.

Trophic biodiversity depends on the number and type of trophic levels (APPENDIX D). Type describes the general life styles of an organism: producer, consumer, detrivore, etc. Number counts the levels of consumption above primary producer. In an ecosystem where cows eat grass and wolves eat cows, the grass would be a producer (P) while cows and wolves are first (C1) and second level consumers (C2), respectively. Within a defined industrial habitat, one could group businesses in a similar way, placing agricultural and extractive industries at the start of an industrial trophic chain.

3.7.2 Ecosystem Engineers

The notion of environmental impact links ecosystem engineers and EBDM. Humans often view themselves as the only organisms capable of engineering, but as Jones and coauthors seminal paper argues, a host of other organisms engineered and continue to engineer Earth's surface, energetic fluxes and material cycles (Jones, et al.

1994). Not unlike man's works of engineering, the works of his fellow organisms impact the environment, changing conditions for the engineer as well as other organisms. Impacts vary in spatial extent and duration. Some ecosystem engineering even outlasts its engineers, causing impacts long after the initiating population's expiration. Differences between ecosystem engineers lead to differences in impact extent, duration and presumably magnitude. A critical part of assessing the environmental sustainability of humanity's products involves assessing environmental impact. Identifying which ecosystem engineering actions lead to longer more extensive impacts may help one identify human design and manufacturing choices with greater potential for environmental impact. Stating this idea as a guideline:

Screen environmental impact severity by comparing ecosystem engineering and human engineering state changes.

Acting upon this imperative requires a three step process. First, one must estimate impact severity for ecosystem engineers. Impact severity estimates allow one to rank the works of human engineering against a biologically based scale. Second, one identifies the resource flows modulated by ecosystem engineers. The second step relates impact to physical quantities. Finally, one relates the works of human and ecosystem engineering.

3.7.3 Weaving Eco-Industrial Webs

The words resources, nonrandom and architecture immediately draw one's attention when reading the principle stated in Section 3.5.3. The first word connects living networks and industrial ones while the latter two encapsulate the guidance given by the former. Both network types transfer material, energy and even information resources. The nonrandom patterns of nodes and links commonly found in living interaction webs represent architecture design guidance for industrial networks. Capturing this guidance in the form of network metrics allows one to set measurable goals for the holistic biomimetic design of industrial networks.

Ecosystems and industrial systems transfer resources between independent organizational entities. Organisms transfer material and energy by consuming each other; pollinators pass genetic information between plants. Businesses sell products, energy and information to other businesses, government institutions or consumers. In each system, one can define the node as an organism or a business and resource transfers constitute links. Industrial ecology, the field of study originally born from the "waste equals food" analogy drawn from living systems, typically takes individual corporations as the smallest distinct organizational unit in industrial systems (Ayres 1994). While a reasonable approach to industrial node denotation, a more directly analogous one is the definition of a node as a largely self-contained stock of material, energy or information. This more physical definition relates biological metrics to industrial situations in this section and serves as the starting point for modeling efforts in later chapters. It should be noted that defining nodes as self-contained stocks does not prevent the use of firms as nodes; it merely provides a finer resolution that more clearly bridges the gap between firm and organism. Having discussed the connection between ecosystems and industrial systems provided by resources, one can contemplate the value of living network architectures in industrial systems.

Life's multi-billion year track record of persistence and success proved its capacity to effectively utilize Earth's resources. Interest in biologically rooted ideas such as "waste equals food" proves engineering's interest in life's track record, but grasping the basic notion and designing an artificial system that embodies it are different matters. Design entails specification of network node types, connections between nodes, connection capacities and other structures. One wants the resultant network to not only fulfill its intended function and use resources effectively but also remain stable in the event of resource fluctuations or node loss. Living networks faced, survived and flourished despite similar challenges. Patterns repeatedly appearing in living networks represent a design template for achieving environmentally sustainable resource distribution despite perturbations. One might summarize the lesson for systems engineering as:

Imbue industrial resource distribution networks with common living network patterns.

Clusters of nodes and links in biological interaction webs often appear every bit as tangled as the creatures on Darwin's imaginary bank. One first needs a means of discerning patterns in these interaction tangles if one intends to eventually imbue industrial networks with their patterns. Thankfully, ecologists employ a host of metrics when analyzing interaction web structures and dynamics. These metrics fall into three categories: static structural, web dynamics and structural dynamics. One can directly apply some of these to industrial resource networks and compare the values obtained with their ecological counterparts. Here, each metric category is described, and associated metrics are briefly discussed. Given the number of potentially applicable metrics, detailed development of selected metrics in the context of specific engineering situations occurs in later chapters.

Static structural measures and metrics form the first category of interaction web metrics found in the biological sciences. Focusing solely on network structure, they provide information about patterns formed by links between nodes at a particular time. The focus on abstract structure permits direct application to industrial networks. In fact, Hardy compared ecosystem connectance values with those of industrial ecologies and ecoparks (Hardy, et al. 2002). Knowledge of the total number of links (L) and nodes (S) in an entire network or particular areas of a network permits their calculation. Measures and metrics of this type include: path length, trophic ratios, connectance, specialized predator ratio, link density, and cyclicity (See Table 9). Recent work in ecology also examines the distribution of links per node in a network (Jordano, et al. 2003). Given a graph, one can determine distributions of this type for other networks.

Table 9: Selected Static Structural Metrics for Interaction Webs

Measure or Metric	Means of Calculation	Biological Note
Path Length	Addition of number of links between two nodes	• Constant, though with high variance, for observed food webs (Pimm, et al. 1991)
Trophic ratios	Proportions of species at trophic levels and proportions of links between trophic levels	
Connectance	$c_{con} = L/_{S(S-1)}$ for no cannibalism $c_{con} = L/_{S^2}$ for cannibalism	• Patterns discernable in food webs but causes debated (Warren 1990)
Specialized Predator Ratio	$p_{special} = {}^{n_{s-pred}}/_{n_{predator}}$	• (Hardy 2001)
Link Density	$L_d = L/_S$	• (Warren 1990)
Cyclicity	Determined by calculating the maximum eigenvalue of an adjacency matrix for nodes exchanging material	• High cyclicity observed for food webs when detritus material paths included (Fath 2007)

Metrics accounting for web dynamics focus on rates of change within a given structure of nodes and links. They incorporate steady-state and transient dynamics. Steady-state web dynamics metrics for material and energy flows are based on input-output mathematics originally developed by Leontief for economic analyses (Leontief 1936, Finn 1976, Patten 1985). Since they deal with physical quantities common to both ecological and industrial networks, these metrics directly apply to industrial situations. For steady-state material flows, Bailey translated these ecological metrics into industrial equivalents (Bailey, et al. 2004a, b). Transient dynamics modeling first occurred in a complete form in May's work on system stability (May 1972). In these models, one calculates eigenvalues for interaction matrices to learn a particular community's stability. Negative eigenvalues indicate a community's ability to return to equilibrium if perturbed while positive values indicate the opposite. Interaction strengths represent the effect of one species on the growth rate of another (Montoya, et al. 2006). In this context, stability refers to the viability of species populations that constitute the nodes linked together by interaction strengths. Unfortunately, growth rate influence and species population lack obvious corresponding quantities in industrial networks.

The structural dynamics category deals with changes in the node and link structure of networks. Ecologists tend to concentrate on node loss (species extirpation) and gain (species invasion). They conduct static and dynamic community viability analyses. The static analysis involves deletion or insertion of nodes into a web. Node deletion clearly reveals interaction web disintegration, but further local extinctions wrought by changes in web dynamics remain hidden (Ebenman, et al. 2005). One needs to develop transient dynamic models for the modified network to gage the stability of the modified system. Static viability analysis in an industrial context is an analogous affair; removing nodes from an industrial network can fragment it. However, dynamic viability is not directly comparable because population size and growth rate influence lack direct physical analogs in industrial networks.

3.7.4 An Intensive Energy Consumption Limit

In the context of design for environmental sustainability, one could interpret the presence of metabolic limits observed across diverse species (Makarieva, et al. 2005b) as the bounds for safe, sustained energy consumption per unit mass on Earth. Such metabolic bounds may represent the constraints written of by Lotka and Chaisson beyond which further energy consumption destroys a system (Lotka 1922a, Chaisson 2001). Leaving aside controversial ideas about maximum power, one may state this potential principle as:

Limit the rate of energy consumption per unit mass.

One can readily translate this qualitative, potential principle into a quantitative form amenable to engineering design problems. Energy consumption rate per unit mass serves as a metric that gages conformance with the limit on energy flows accepted by living systems. As discussed in Section 3.5.4, work in biological energetics sets the average, maximum acceptable value for sustained energy consumption per unit mass at roughly 40 W/kg (Makarieva, et al. 2005a). In engineering design, one could use this specific energy consumption rate metric and its biologically derived limit as a constraint in a design space. Design spaces, the set of all design variable configurations, contain environmental as well as traditional engineering constraints. One could also use specific energy consumption rates as a simple means of partially assessing whether a product, process or system consumes energy in a sustainable manner.

3.7.5 Surface Suggestions

Life's principle of surface adhesion modification requires little translation and minor modification. Many engineered objects need to remain clean; therefore, surfaces that promote cleanliness are directly applicable. Less cleaning and less intense cleaning benefit the environment by avoiding resource consumption and reducing cleaning waste burdens. The principle stated in Section 3.5.5 focuses on surface chemistry and geometry. The surfaces in question use micro and nano-scale geometry to enhance properties initially imparted by surface chemistry. Small scale geometric changes transform hydrophobic surfaces into superhydrophobic surfaces. And, it is this point that needs modification in an engineering context.

Organisms evolved in a wet world with particulate and aqueous contaminants. Biological solutions that led to the statement of the principle in Section 3.5.5 largely use hydrophobic surface chemistries. Evolution matched surface chemistry to the solvent of the most likely contaminants and enhanced it with geometry. In engineering applications, water is not always the most likely contaminant carrier. Something as ordinary as a car engine contains parts soiled by oils and materials carried by oils. Oleophobic surfaces might resist contamination and clean easier in such circumstances. To reduce the cleaning burden in an engineering application, one should use surface chemistries repellent to the most likely contaminant carrier and enhance them with micro and nano-scale geometry.

Modulate adhesion using contaminant carrier phobic surface chemistry enhanced by micro and nano-scale structures.

The metric embodying the modified principle mirrors the simplicity of its translation. Qualitative and quantitative observations of the contact angle (θ_c) formed by a contaminant carrier with a surface provide insight into the cleaning burdens it might generate (See Figure 20).

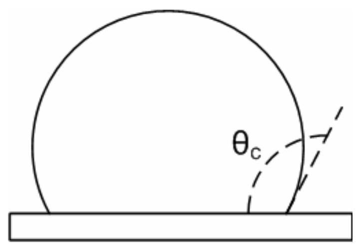

Figure 20: Drop with a Phobic Contact Angle

When contact angles for a fluid on a surface exceed 90°, one generally considers them phobic contact angles. Surfaces exhibiting highly phobic contact angles ($>150^\circ$) for contaminant fluids or contaminant carrying fluids stand a better chance of remaining clean or self-cleaning once soiled. Simply measuring the contact angle for parts or products of interest provides insight into the cleaning maintenance and associated environmental burdens one might expect.

3.7.6 Succession – Setting the Direction for Environmental Progress

Many bio-inspired sustainable engineering principles introduced in Section 3.7 describe goals or preferred end states for systems. In contrast, direction of change is the prevailing idea behind succession. The discussion in Section 3.5.6 reveals that communities in many ecosystems tend to change in comparable ways. They progress toward more specialized, efficient and organized communities of organisms within limits such as climate, disturbance regime and available colonists. The biological principle in Section 3.5.6 represents an arrow of change. It provides those attempting to organize multiple, independent industrial entities with an idea of the environmentally sustainable direction of change. One might state the environmentally sustainable change guideline as:

Progress toward greater specialization, efficiency, and organization of industrial networks

Many metrics for this succession based guideline already appear in Section Section 3.7. Diversity measures and metrics introduced in Section 3.7.1 provide insight into a network's level of specialization. One expects increasing specialization to track increasing diversity. Energetic and material efficiencies for networks of interacting entities were mentioned in relation to resource networks in Section 3.7.3. In the cases of both specialization and efficiency, the succession guideline indicates that one moves toward a more environmentally sustainable state when the values of these metrics and measures indicate increasing diversity and efficiency. The succession guideline instructs the analyst or designer to pay attention to trends.

One could use some of the structural metrics presented in Section 3.7.3's Table 9 to visualize trends in organization, but a metric that more completely capture's Odum's thoughts about ecosystem succession exists (Odum 1969, 1987). Ulanowicz combines trophic material flow concepts and information theory to create a metric dubbed Ascendancy (A) (Ulanowicz, et al. 1997). According to Ulanowicz, Ascendancy increases as succession proceeds (Ulanowicz, et al. 1997).

$$A = R\sum_i \sum_j \left(\frac{R_{ij}}{R}\right) \log\left(\frac{R_{ij}R}{\sum_q R_{iq} \sum_r R_{rj}}\right) \tag{3}$$

In the Equation 3, R is the sum of all trophic flows in the ecosystem, and R_{ij} is the flow from compartment i to compartment j. The term $\frac{R_{ij}}{\sum_q R_{iq}}$ is a conditional probability. The Ascendancy metric captures sheer growth of an ecosystem using R and increased organization using the remainder of the function.

3.8 Tenets of EBDM and Holistic Biomimicry Compared

Main tenets extracted from EBDM literature are compared and contrasted with the translated principles. The extent to which similarities between the two exist serves as a form of validation.

3.8.1 EBDM Study Parameters and Literature Selection

As discussed in Section 3.2, one needs to set a few study parameters prior to employing Constant Comparative Method or its elements. Table 5 lists these parameters and their settings for the analysis of EBDM literature.

Table 10: EBDM Study Parameters and Settings in this Dissertation

#	Study Parameter	Setting
1	Studied source material (i.e. site, group, etc.)	Design for environment, environmentally conscious / benign manufacturing and industrial ecology literature
2	Data types	Book sections, journal papers and conference articles from academic works
3	Number of sites / observations	Arbitrarily set at 100 book sections, journals and articles
4	Study length	Time required to review the number of specified works
5	Foundational and motivational research questions	Research Question 2 in Chapter 1

Four categories of sustainable engineering literature form the pool of source material. The first category encompasses literature advancing principles, guidance and general rules for EBDM. The second type addresses environmental sustainability concerns from the perspective of the engineering knowledge process, the plan for design, creation and use. The third type partially overlaps the second; it contains literature about the life cycle of human artifacts from material extraction through use to end of life disposition. The final category consists of literature dealing with sustainability concerns at different organizational scales of engineering relevance (material, part feature, component, product, facility, multi-facility).

Filling these categories involved searching online databases, specific journals and libraries. General texts, respected journals and sections of journals known to contain information falling into one or more of the four categories were searched. Reviewed journals included: Environmental Science and Technology, Journal of Cleaner Production, Journal of Industrial Ecology, Ecological Engineering and Resources Conservation and Recycling. Special sustainability issues and conferences of more general engineering journals and societies such as the Journal of Mechanical Design, ASME and IEEE also yielded literature. Online databases such as Compendex and the

Web of Science were searched. Searches used general keywords such as principle, theory, rule and generalization and EBDM oriented keywords such as life cycle, environmental impact, and sustainability. Similar keywords formed queries used when accessing the Georgia Institute of Technology library catalog and the Institute for Sustainable Systems' library.

3.8.2 Extraction of EBDM Guidance

Applying the approach presented in Section 3.4 to EBDM literature, one extracts the underlying themes from code memos found in APPENDIX E. One begins by observing the frequency with which identified concepts recur in the sample of EBDM literature (See Figure 21).

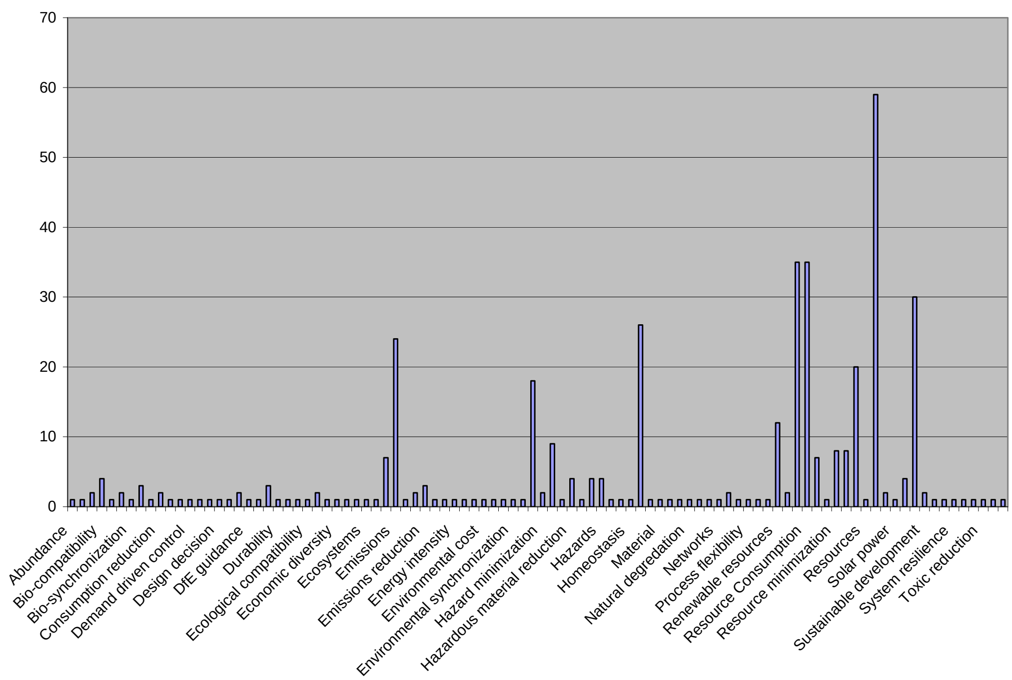

Figure 21: Frequency of Concepts Encountered during Coding of EBDM and Sustainability Literature

The coding process identified many concepts in the sampled EBDM and sustainability literature, but only a limited number frequently occur. Concepts in Figure 22 recur with

greater frequency than most and each concept appears in ~4% or more of the sampled literature. While all of those listed in Figure 22 are encompassing, some concepts, such as life cycle and sustainability, describe hopelessly expansive EBDM ideas. A number of other concepts label similar phenomena. Eliminating the ineffectually broad and grouping the related, one generates categories of prevalent EBDM concepts found in the sampled literature (See
Table 11).

Before proceeding to explain the identified categories, it is important to note that the coding experience for EBDM literature differed from that of biology literature. Saturation, the term used in CCM literature for the point at which no new information about a category appears during coding, defines this difference (Strauss, et al. 1998). The same coding and analysis process applied to both, but EBDM coding reached saturation in terms of concepts, properties and dimensions while biology coding did not. In this author's opinion, dominant EBDM categories appeared and saturated within the first 30-40 units of the sample. Coding the biology literature could have productively continued beyond the sample of ~100.

The difference in coding experiences has at least two implications for this study. First, achievement of saturation during EBDM coding indicates that the review was comprehensive. Second, the difference between the two experiences highlights the difference in maturity between the two fields and, importantly, suggests that biology remains a source of inspiration for EBDM that one can continue to mine.

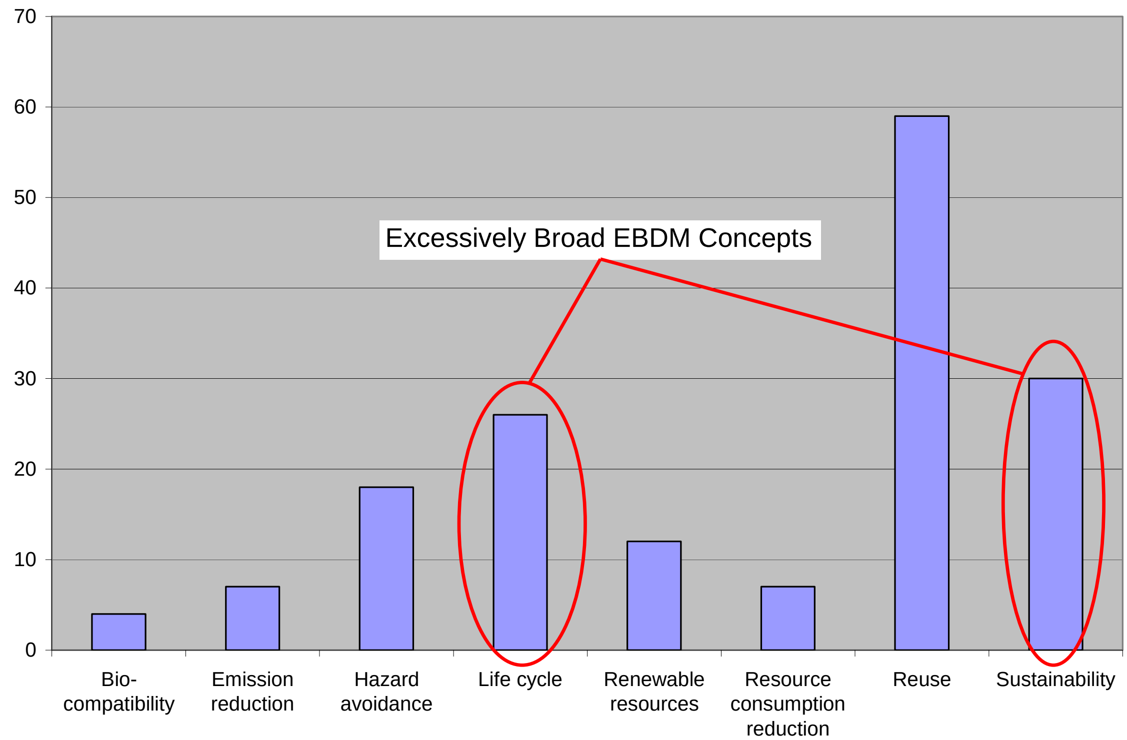

Figure 22: Frequency of recurring EBDM concepts

Table 11: EBDM Categories

Initial Categories	Number of References	Number of Related Concept Occurrences	% of References
Bio-compatibility	4	10	10.0%
Emission reduction	7	38	38.0%
Hazard avoidance	18	51	51.0%
Renewable resources	12	15	15.0%
Resource consumption reduction	7	84	84.0%
Reuse	59	60	60.0%

Each category in

Table 11 contains related concepts, properties and dimensions identified during open coding. One can interpret them as general prescriptions from the EBDM research community for curing the industrial system's environmentally unsustainable ills. Each category label represents a wealth of ideas to the coder that may not be apparent to the reader. To reduce the knowledge gap, Table 12 contains a brief description of each.

Table 12: Description of EBDM categories

Category	Description
Bio-compatibility	Bio-compatibility is the capability of an engineered artifact or process to participate in biogeochemical cycles without damaging ecosystems or their constituent organisms. Most related EBDM references focus on the ability or lack of ability of materials to degrade.
Emission Reduction	This category captures the community's continued interest in end-of-pipe pollution. However, the concept encompasses more than a simple concern with outflows to traditional media (air, water and land) generated during major industrial activities such as resource extraction and manufacture. It importantly prescribes reduction, not merely treatment, of emissions. It incorporates concern for non-point source emissions and those associated with product life cycles.
Hazard avoidance	The Hazard Avoidance category exists as a result of the EBDM community's belief that one must avoid using hazardous materials, intermediaries and processes to deliver goods and services. Though the path from technology to harm is not always clear, the hazard in question is usually a threat to human health, organism health, ecosystem function or an abiotic system that can damage the others. Many references deal with toxic substances or "substances of concern" used as products or in products.
Renewable resources	This category is a simple call to use renewable sources of material and energy to provide humanity with goods and services. Many of those mentioning the importance of renewable resources to a sustainable society also caution that excessive resource extraction rates can turn a renewable resource into a nonrenewable one (i.e. collapsing fisheries).
Resource consumption reduction	Resource consumption reduction deals with the need to cut society's usage of material and energy as well as strategies to achieve such an end.
Reuse	Reuse refers to the EBDM community's recommendation to reuse the material outputs of the industrial system and to find cascading uses for energy flowing into it. Reuse incorporates calls to recover, repurpose, refurbish, remanufacture and recycle materials. Material could be: scrap, waste, parts, products or even structures. References included in this category also mention the infrastructure needed to support new material flow networks.

3.8.3 Comparing Bio-inspired and EBDM Guidance

Comparing the six bio-inspired EBDM guidelines with the major prescriptions found in EBDM literature, one finds similarities and differences. Similarities appear in the actions prescribed, but this correspondence is not evenly distributed among the guidelines. The two sets differ in that some important EBDM categories lack corresponding bio-inspired principles. However, none of the differences in the two sets leads to mutual exclusion. The differences serve more to highlight implicit assumptions in the science of biology than deficiencies in the bio-inspired list presented in Table 13.

The first two guidelines found in Table 13 correspond with the resource consumption reduction category found in EBDM literature. The first guideline in Table 13 offers the hope that one can reduce resource consumption by reducing cleaning burdens through adhesion modulation. Unlike some of the other guidelines, the EBDM literature's support for adhesion modulation is indirect. The mass specific energy consumption restriction found in Table 13's second guideline is a specific form of the call to reduce resource consumption. One finds similar recommendations in nature and engineering at the product / organism and, potentially, product feature / sub-organism organizational scales.

The two bio-inspired guidelines dealing with the efficiency and organization of industrial networks tend to push industrial systems toward less resource consumption, fewer emissions and greater reuse. Increases in product and process efficiency are often viewed as a sound way to improve the environmental character of the industrial system, and this is a recommendation explicitly present in Table 13's sixth guideline. Organizing industrial resource distribution networks in more biological forms would, on the surface, lead to more interconnections. This in turn would lead to the use of more wastes as inputs, reducing emissions and increasing material reuse and energy cascading. At the organizational level of multiple independent actors, nature and environmentally benign engineering qualitatively agree.

Interestingly, important EBDM literature categories of bio-compatibility, hazard avoidance and renewable resources lack counterparts in the list of bio-inspired guidelines. The absence of these categories suggests the existence of two implicit assumptions in biology:

1. Living material and processes are inherently compatible
2. Solar irradiance, tidal potential and geothermal heat power the living world

Studies of organisms and ecosystems in recent geological time do not mention material incompatibility or hazardous substances because researchers assume the compatibility of present materials and processes. Similarly, the importance of solar thermal energy and photosynthesis to biogeochemical cycles is without question and would not explicitly appear in most publications. A coder would not find references to either important assumptions, or too few references to them would appear to attract his attention. As a consequence, he would pass over both. Such an outcome does not invalidate any findings from the coding exercise, though. It primarily serves to highlight ways to improve its accuracy through targeted literature sample selection.

Overall, a comparison between guidance from EBDM literature and biology lends moderate support to the stated guidelines. This outcome partially validates the bio-inspired EBDM guidelines from an engineering perspective. However, quantitative application is needed to further validate them.

3.9 Biological Principles and Bio-Inspired Guidelines

The previous sections of Chapter 3 extracted and developed principles and guidelines listed in Table 13. Table 13 reorganizes the six principle-guideline pairs by organizational scale of applicability. Table 14 contains guidelines removed from the list on the grounds of practical burdens in further validation or limitations in the biological case.

Table 15 holds the pairs of principles and guidelines selected for further validation.

Table 13: Biological Principles and EBDM Guidelines Organized by Organizational Scale of Influence

#	Scale	Biological Principle	EBDM Guideline
1	Sub-Organism	Life modulates adhesion using hydrophobic micro and nano scale structures.	Modulate adhesion using contaminant carrier phobic surface chemistry enhanced by micro and nano-scale structures.
2	Organism	Life accepts a limit on mass specific metabolic rate.	Limit the rate of energy consumption per unit mass.
3		Ecosystem engineers impact their environments through physical changes of state.	Screen environmental impact severity by comparing ecosystem engineering and human engineering state changes.
4	Multi-Organism	Life distributes and retains resources using nonrandom network architectures.	Imbue industrial resource distribution networks with common living network patterns.
5		Life maintains and enhances ecosystem functionality by maintaining and enhancing biodiversity.	Maintain and enhance industrial network functionality by maintaining and enhancing economic diversity.
6		Ecosystems tend toward greater interaction specialization, energy storage, trophic efficiency, recycling structure and organism life span.	Progress toward greater specialization, efficiency, and organization of industrial networks.

Table 14: Eliminated Guidelines

Scale	EBDM Guideline	Reason for Elimination
Organism	Screen environmental impact severity by comparing ecosystem engineering and human engineering state changes.	Though biologically valid, the task of identifying impacts for each organism represents a cost in outsized proportion to the benefit it might render to this dissertation.
Multi-Organism	Maintain and enhance industrial network functionality by maintaining and enhancing economic diversity.	Underlying biological principle insufficiently defined
	Progress toward greater specialization, efficiency, and organization of industrial networks.	Underlying biological principle found to be biased toward older interpretations of ecological data

Table 15: Guidelines selected for further validation

#	Scale	Biological Principle	EBDM Guideline
1	Sub-Organism	Life modulates adhesion using hydrophobic micro and nano scale structures.	Modulate adhesion using contaminant carrier phobic surface chemistry enhanced by micro and nano-scale structures.
2	Organism	Life accepts a limit on mass specific metabolic rate.	Limit the rate of energy consumption per unit mass.
3	Multi-Organism	Life distributes and retains resources using nonrandom network architectures.	Imbue industrial resource distribution networks with common living network patterns.

Statement and organization of the guideline pairs in

Table 15 marks the finish of the dissertation's purely intellectual synthesis. It stands at the work's midpoint on the dividing line between a proposed philosophy of sustainable design and the

engineering tests that wille valuate it. It opens the way for the dissertation's technical development and quantitative validation of these ideas in the remaining chapters. Quantitative validation begins in Chapter 4 where the first of the guidelines in

Table 15 is tested via physical experiments.

CHAPTER 4: ENVIRONMENTAL EFFICACY OF PHOBIC SURFACES WITH SMALL SCALE STRUCTURING

Chapter 4 begins the evaluation process for the biological principles extracted and translated in Chapter 3. This chapter represents the first physical test of the dissertation's overarching proposition that the application of biologically rooted principles in the form of engineering guidelines leads to environmentally superior outcomes. Specifically, Chapter 4 evaluates the environmental efficacy of the design guideline:

Modulate adhesion using contaminant carrier phobic surface chemistry enhanced by micro and nano-scale structures.

Efficacy determination consists of applying the guideline and measuring the resultant environmental burden reductions, if any. Experiments of relevance to industrial and commercial cleaning situations quantify its efficacy. Statistically significant burden reductions lend support to the imperative's efficacy which in turn reinforces the dissertation's overall proposition.

Section 4.1 begins the efficacy determination process by describing the guideline's application and the EBDM motivation for this particular case. Importantly, this section also introduces two testable hypotheses that allow one to quantify the environmental value of the stated imperative. Section 4.2 describes the method, procedures and apparatus used to test the hypotheses introduced in Section 4.1. Results and analysis of these tests appear in Section 4.3 while Section 4.4 discusses these results.

Section 4.5 concludes the chapter by reflecting upon the expected outcome in light of the experimental results.

4.1 EBDM Motivation and Hypotheses for Self-Cleaning Surfaces

Product surfaces become soiled during use, and components contaminated by cutting fluids, coolants and chips sometimes require cleaning between (re)manufacturing operations. At best, cleaning restores the value of a product. Cleaning operations conducted between manufacturing steps do not add value. Cleaning is, therefore, something worth minimizing during product and component life cycles.

Surfaces that resist soiling or ease contaminant removal enjoy advantages over standard surfaces in terms of reduced energy, material, temporal and monetary resources required to maintain cleanliness levels. Savings in physical resources likely spurred the evolution of self-cleaning surfaces in multiple organisms. Roughly 200 plant species (Barthlott, et al. 1997), 90 species of insects (Wagner, et al. 1996a), Geckos (Hansen, et al. 2005) and even Pilot Whales (Baum, et al. 2002b) combine hydrophobic surface chemistry's and micro/nano-structured geometries to create self-cleaning surfaces. The behavior of water droplets on Lotus plant leaves (*Nelumba nucifera*) illustrates this phenomenon (See Figure 23).

Figure 23: Water droplet on Lotus Leaf (2005a)

These surfaces bead water and reduce the area available for effective contaminant adhesion (Barthlott, et al. 1997). Water readily rolls off of these surfaces and removes contaminants in the process. These clear qualitative advantages led researchers to develop means of creating artificial surfaces exhibiting the self-cleaning phenomenon.

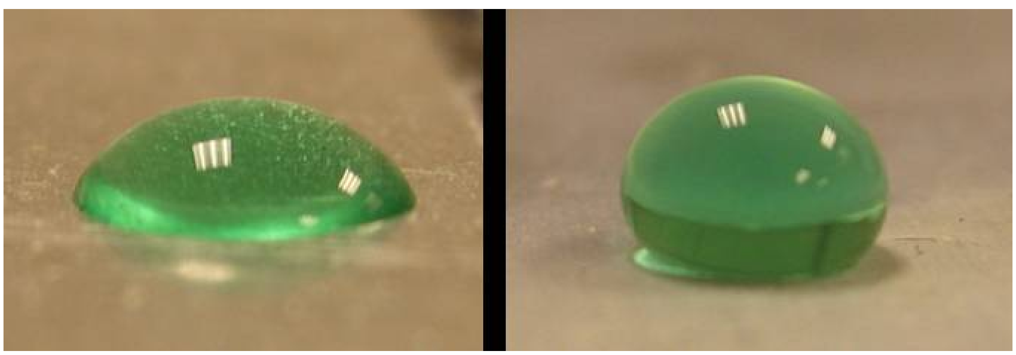

Figure 24: Dyed water on uncoated (left) and coated Al surfaces (right)

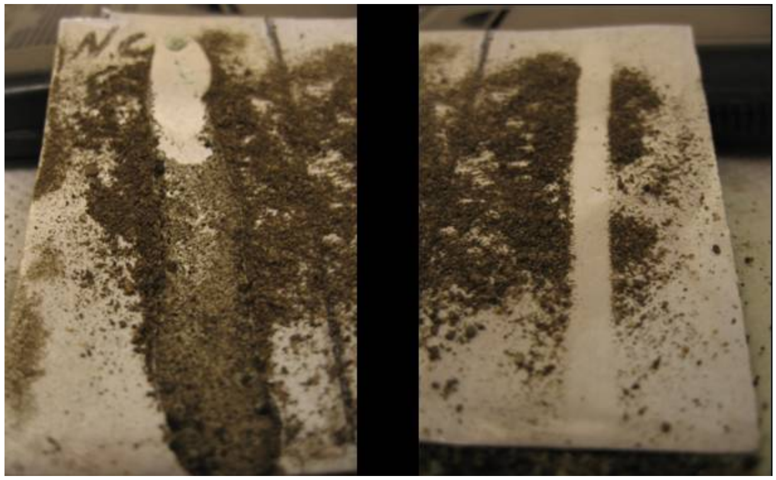

Figure 25: Soiled uncoated (left) and coated (right) surfaces partially cleaned with water

TegoTop® is one such coating. As Figure 24 and Figure 25 reveal, TegoTop® imparts hydrophobic and self-cleaning properties to surfaces. The difference between the two surfaces in Figure 25 clearly illustrates the sought qualitative advantages. However, the potential cleaning resource reductions associated with the application of such surfaces remain without quantitative support in the open literature. The majority of published articles deal with the creation of micro and nano scale surface roughness, hydrophobic chemistries and the modeling of the interaction between single drops and micro/nano-rough surfaces (Oner, et al. 2000, Zhu, et al. 2005, Groenendijk, et al. 2006, Xiu, et al. 2006). Quantifying cleaning resource reductions resulting from the use of self-cleaning surfaces is a primary objective of this chapter.

Resource reductions occur when one avoids cleaning or can clean less intensively. A surface that resists contamination more effectively might require fewer cleanings during its service life. Soiled surfaces might also differ in the amount of cleaning effort needed to remove contaminants. The two ways in which a surface might reduce cleaning resource usage suggest two distinct hypotheses and associated statistical tests.

One directly gages soiling resistance by measuring contaminant levels following soiling. Surfaces that acquire less contaminant during a uniform soiling process exhibit greater resistance. Such surfaces would require fewer cleanings and, therefore, would consume fewer resources. Soiling standard specimens and those with self-cleaning surfaces generates two data sets with contamination mass means that one can compare using a two-sided t-test. Taking the contamination mass means of the standard set (μ) and the self-cleaning set (μ_t), one formulates null (H_0) and alternative (H_A) hypotheses.

$$H_0\text{: } \mu - \mu_t = 0 \text{ versus } H_A\text{: } \mu - \mu_t \neq 0$$

A t-test result with p-values $\leq$ 0.01 and $\mu > \mu_t$ would provide strong support for rejection of H_0 in favor of the statement that standard samples acquire more contaminant than those with self-cleaning treatments.

Direct measures of cleaning intensity include material and energy expended per unit part, time, area or contaminant mass. Keeping material, energy and time expenditure constant in an experiment allows one to quantify cleaning intensity in terms of contaminant mass removal. In turn, this procedure allows one to convincingly argue that increases in contaminant removal equate with decreases in cleaning intensity and, therefore, resource consumption. Cleaning soiled standard specimens and those with self-cleaning surface treatments in a uniform way creates two data sets. Mass measurements allow one to obtain the mass of contaminants remaining on each sample after cleaning (m_r). However, one cannot simply use remaining contaminant mass to formulate a statistical hypothesis because resistance to contamination biases the results. Instead, one combines remaining contaminant mass data (m_r) with contaminant mass data for specimens before cleaning (m_{bc}) to calculate the proportion of contaminant (P) removed during cleaning (See Eqn. 4).

$$P_c = \frac{m_{bc} - m_r}{m_{bc}} \qquad (4)$$

Calculating P for standard and self-cleaning specimens generates proportion means μ_P and μ_{Pt} for the respective specimen sets. One uses these proportion means to formulate null and alternative hypotheses.

$$H_0\text{: } \mu_P - \mu_{Pt} = 0 \text{ versus } H_A\text{: } \mu_P - \mu_{Pt} \neq 0$$

A t-test result with p-values $\leq$ 0.01 and $\mu_P > \mu_{Pt}$ would provide strong support for rejection of H_0 in favor of the statement that standard samples shed a smaller portion of contaminant when cleaned than those with self-cleaning treatments. Such an outcome would in turn support the proposition that self-cleaning surfaces demand fewer resources for the same proportion of contaminant removed.

4.2 Testing Surfaces

This section lists supporting apparatus, required materials and procedures used to generate data needed to test the hypotheses formulated in Section 4.1.

4.2.1 Apparatus and Materials

Table 16 and Table 17 list required lab equipment, experiment apparatus and materials. Figure 26 diagrams the apparatus used for soiling and cleaning during many of the experiments.

Table 16: Required Lab Equipment

Item	Amount	Description / Purpose
Precision balance	1	• +/- 0.1 mg sensitivity that preferably displays SI units • Capable of determining mass of samples up to 5 g • Mettler Toledo AB54 used
Oven	1	• Needed to bake a contaminant • Must maintain temperatures of 105 +/- 2 C
Drying oven	1	• Needed to dry specimens following contamination and cleaning.
Sample dipping apparatus	1	An automatic sample dipping device for soiling and cleaning specimens (See also Figure 26 and Figure 27)
4 L Erlenmeyer Flasks	3	Mixing and storing cleaning solution
100 ml beakers	6	Hold Tegotop® contaminants and distilled water during experiments
50 ml beakers	2	Hold cleaners during experiments
Assorted glassware	-	Mixing and transferring contaminants, distilled water and cleaners
Safety Glasses	1	Provide protection from cleaners and, potentially, specimen contaminants
Assorted spatulas and tweezers for handling specimens and chemicals	-	Enough to avoid cross-contamination of chemical containers and specimens

Table 17: Required Materials

Item	Amount	Description
Aluminum samples	300	1 x 1.5 inch rectangles cut from 0.05 inch sheets of Al alloy 3003 (ASTM B209)
Tegotop®	~300 ml	• Self-cleaning surface producing coating • Enough to coat half the required number of samples
Gloves (Latex and Vinyl)	1 box	• Provide protection from cleaners and contaminants • Prevents uncontrolled contamination of specimens
Acetone	As needed	For removal of oily residues and general cleaning of specimens prior to coating and experimentation
Weigh paper	As needed	Prevent soiling of the scale
Wax Paper	1 roll	To hold ingredients and reduce soiling of the work space
Distilled water	8 gal.	Water for cleaning specimens, creating salt solution and diluting detergent
Octyl Phenol Ethoxylate	1 L	Detergent component
EDTA Tetrasodium Salt	500 g	Detergent component
Potassium Pyrophosphate Anhydrous	1 kg	Detergent component

Table 17 continued		
Detergent	9656 ml	• Detergent for cleaning specimens • Solution of distilled water, Octyl Phenol Ethoxylate, EDTA Tetrasodium Salt, Potassium Pyrophosphate Anhydrous
Graphite powder	12 g	• A non-hydrocarbon lubricant • Extra Fine Graphite Dry Lubricant manufactured by AGS
Cutting fluid	1 L	• A contaminant commonly found in manufacturing settings in which machining occurs • A 1L supply would allow us to contaminate each sample with 20 mL of cutting fluid • GreetCut® Cutting / Missting Fluid from Lube Corp Inc.
Polyethylene glycol mixture	3.78 L	• Anti-freeze and coolant; commonly found in automotive applications • Reference ASTM C756-87 • Prestone 50/50 Prediluted Antifreeze / Coolant
Industrial lubricant	1 L	• Oil with viscosity similar to MIL-L-23699 azlubricating oil • SAE 10W motor oil

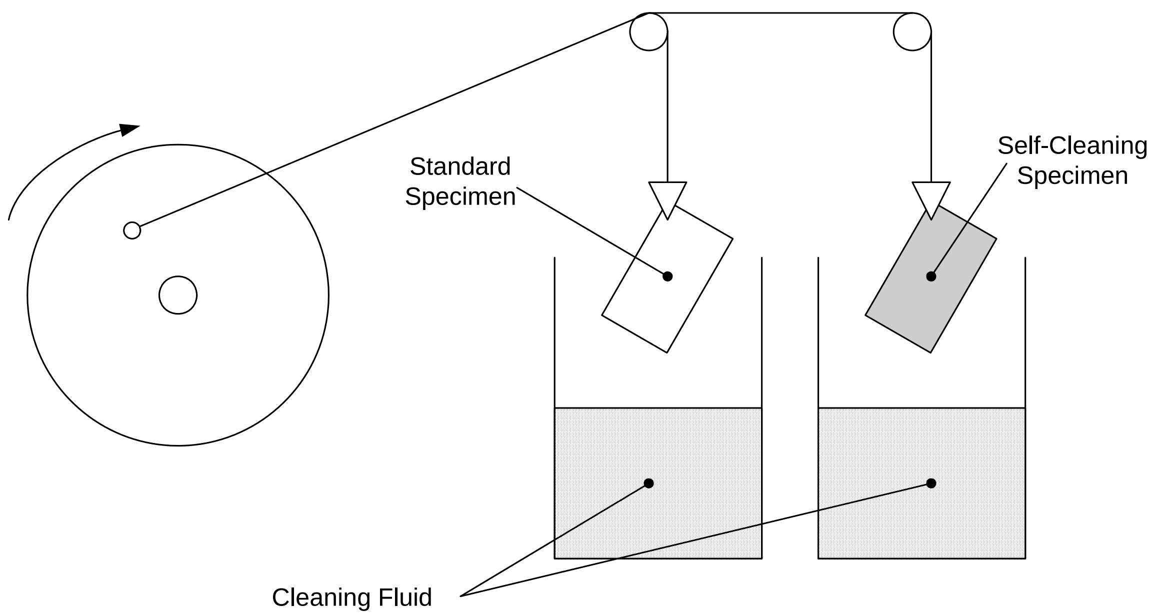

Figure 26: Dipping Apparatus Schematic

Figure 27: Dipping Apparatus

4.2.2 Sample Preparation

An experiment meant to evaluate surface responses to different treatments and contaminants requires attention to the state of the tested surfaces prior to treatment. One must minimize variations in the surfaces introduced by sheet metal production, specimen manufacture and uncontrolled contamination. To control for production variations, specimens can be cut from sheets of the same Al alloy, and one can evenly distribute batch variations by randomly selecting specimens from each sheet. Having obtained samples of the dimensions given in Table 17, one must clean them to remove contaminants introduced prior to treatment. Finally, one must coat half of them prior to the experiment. To summarize:

1. Obtain enough Al sheet metal for the required number of specimens. Order them directly from McMaster-Carr (http://www.mcmaster.com/).
2. Cut sheets into 1.5 x 1 in specimens using the same technique. Place a work order with the MRDC machine shop.
3. Clean all samples with acetone or xylene. Human exposure to xylene must be minimized; so, cleaning must occur in a well ventilated location. Eye protection and vinyl gloves must be worn during the cleaning process.
4. Place some of the TegoTop® in a 100 ml beaker.
5. Dip half of the samples into the TegoTop®.
6. Let the dipped samples dry for at least two days in the open air.
7. Label the back of each specimen with crayon. Specimen pairs will be labeled consecutively with uncoated specimens (red crayon) having odd numbers and coated specimens (black crayon) having even numbers. For instance, the first

specimen will be uncoated and marked with a red number "1" while the second will be coated and marked with a black number "2".

Figure 28 displays one batch of completed specimens ready for contamination and cleaning.

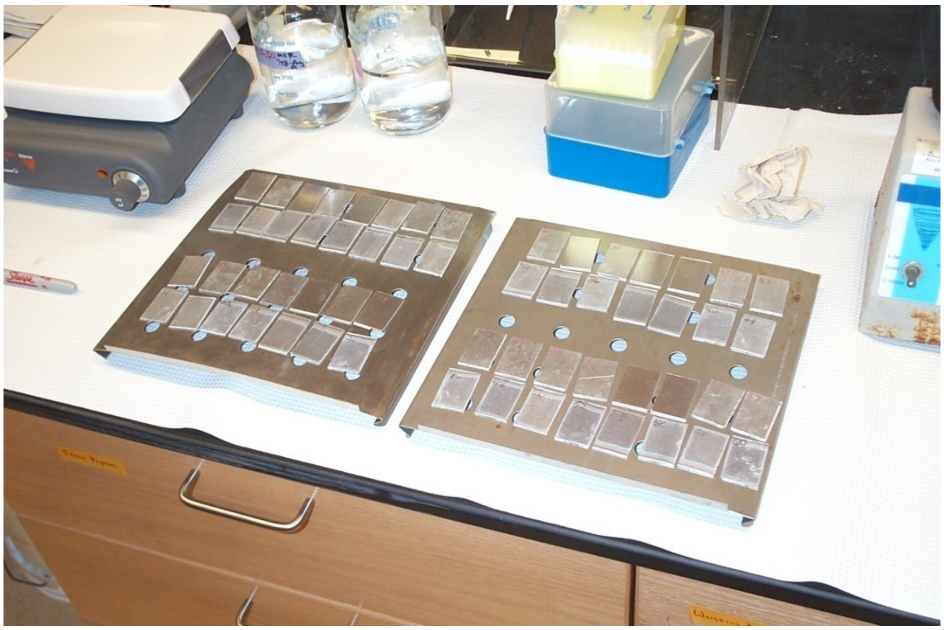

Figure 28: Completed, Unsoiled Specimens

4.2.3 Contamination Resistance Quantification

To quantify soiling resistance, one must establish a baseline for each specimen prior to contamination, soil the specimens and then measure the change. Standards quantify cleanliness in terms of reflectance or mass (SAE 1999, ASTM 2001, ISO 2006). Those relying on reflectance typically apply to residential and commercial applications (ASTM 2001) while mass measurements appear more prevalent in industrial situations (SAE 1999). Mass measurement gages the true level of surface contamination; so, it quantifies soiling in these experiments. Following preparation, each specimen must be weighed using a sensitive scale to establish a baseline. Then, each specimen must be soiled and weighed a second time. The difference between baseline and soiled mass is the contamination level (m_c). Chawla believes a scale accurate to +/- 1 mg is sufficient for this purpose, though SAE recommends a sensitivity of +/- 0.1 mg (SAE 1999, Chawla 2003). These experiments use the more sensitive balance. The following tables detail the procedure for each contaminant.

Table 18: Graphite Powder Contamination Resistance Test

#	Procedure
1	Measure and record mass for each specimen
2	Place 1 uncoated and 1 coated specimen in a container of graphite powder and manually cover with graphite powder (A-D in Figure 29)
3	Invert and then right the container.
4	Retrieve specimens and allow excess graphite to slide off
5	Separately weigh and record the mass of each specimen
6	Repeat steps 1-5 until all specimens contaminated
7	Proceed to cleaning plan outlined in Section 4.2.4

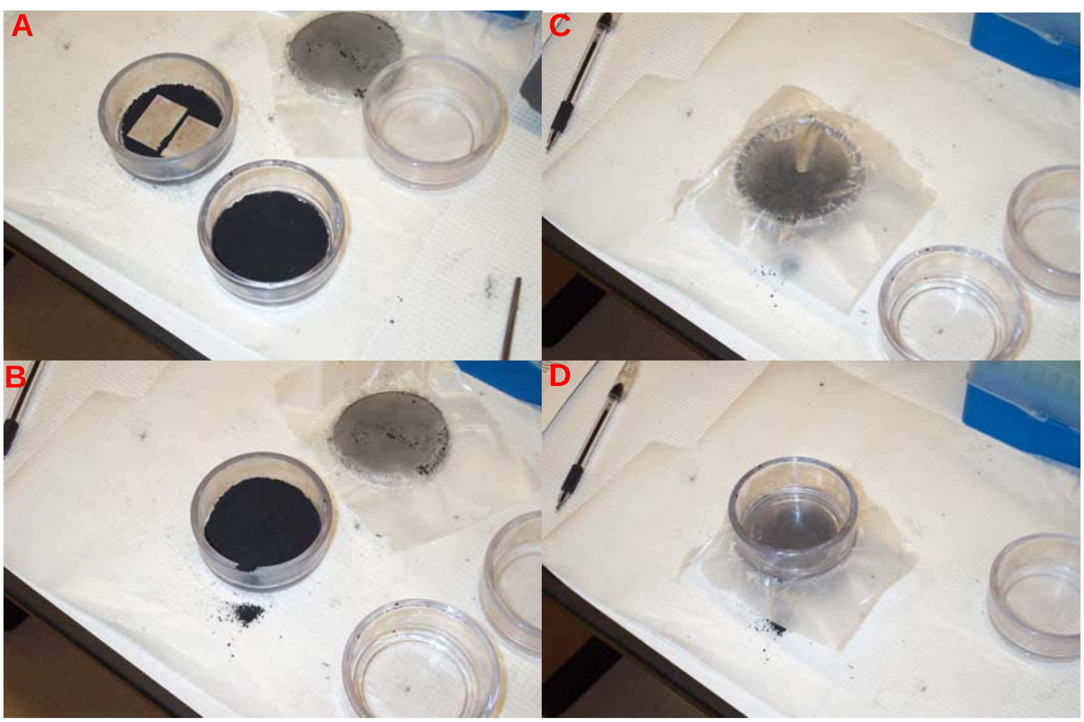

Figure 29: Graphite Powder Contamination Process

Table 19: Brine Contamination Resistance Test

#	Procedure
1	Create 0.90 M salt solution by dissolving 25.0505 g NaCl in 400 ml of distilled water.
2	Weigh and record the mass of each specimen.
3	Lay specimens flat on a tray.
4	Apply 1.5 ml of salt solution to the center of each specimen using a 5 ml syringe with 0.2 ml graduations. The point of the syringe should remain in contact with the drop during deposition of the brine solution.
5	Evaporate the water in the brine solution by air and oven (65 C) drying.
6	Weigh and record specimen mass.
7	Proceed to cleaning plan outlined in Section 4.2.4.

Table 20: Oil Contamination Resistance Test

#	Procedure
1	Measure and record mass for each specimen
2	Attach 1 uncoated and 1 coated specimen to the dipping apparatus described in Section 4.2.1
3	Fill two beakers with fresh SAE 10W motor oil.
4	Run the dipping apparatus for 3 min.
5	Remove specimens and set aside
6	Repeat steps 2-5 until each specimen has been coated with lubricant.
7	Place specimens in oven heated 105 $\pm$ 2 C for 1 hr.
8	Air cool to room temperature
9	Weigh and record specimen mass, changing weigh paper after every 3 specimens. Make certain to tare the scale after weighing each specimen.
10	Proceed to cleaning plan outlined in Section 4.2.4.

Table 21: Polyethylene Glycol Contamination Resistance Test

#	Procedure
1	Measure and record mass for each specimen
2	Attach 1 uncoated and 1 coated specimen to the dipping apparatus described in Section 3.1
3	Fill two beakers with Prestone 50/50 Anti-freeze.
4	Run the dipping apparatus for 3 min.
5	Repeat steps 1-4 until each specimen has been coated with anti-freeze.
5	Dry specimens for 1 hr. at 65 C.
6	Air cool to room temperature
7	Weigh and record specimen mass, zeroing the scale and changing weigh paper as needed.
8	Proceed to cleaning plan outlined in Section 4.2.4.

4.2.4 Quantifying Ease of Cleaning

Testing the second hypothesis formulated in Section 4.2.3 requires determination of contaminant mass remaining on each specimen following cleaning. Having soiled the specimens using the procedures in the previous section, one must clean them using a controlled process. The apparatus sketched in Figure 26 washes specimens in this experiment and is based on one used by SAE AMS-C-29602 to wash similar metal plates in a controlled fashion (SAE 1999). Figure 30 shows two specimens in the dipping apparatus. Washed specimens are oven dried and weighed after cooling. Specific cleaning and data acquisition procedures for particulate, brine and other liquid contaminants appear in Table 22 and Table 23.

Table 22: Procedure for Cleaning Particulate and Brine Contaminants

#	Procedure
1	Attach 1 of each type of soiled specimen to the dipping apparatus
2	Fill two 100 ml beakers with distilled water and place in the dipping apparatus
3	Run dipping apparatus for 5 mins. at 20 $\pm$ 1 cycles/min.
4	Remove specimens
5	Note any visible changes in contamination level
6	Set aside and return to step 1
7	Repeat steps 1-6 until all specimens have been cleaned or enough cleaned specimens for an oven batch have been generated
6	Oven dry specimens for 1 hr. at 65 $\pm$ 2 C (**Brine only**: Air and oven dry brine contaminated specimens until completely dry.)
7	Remove specimens and allow to air cool.
8	Weigh and record specimen masses.

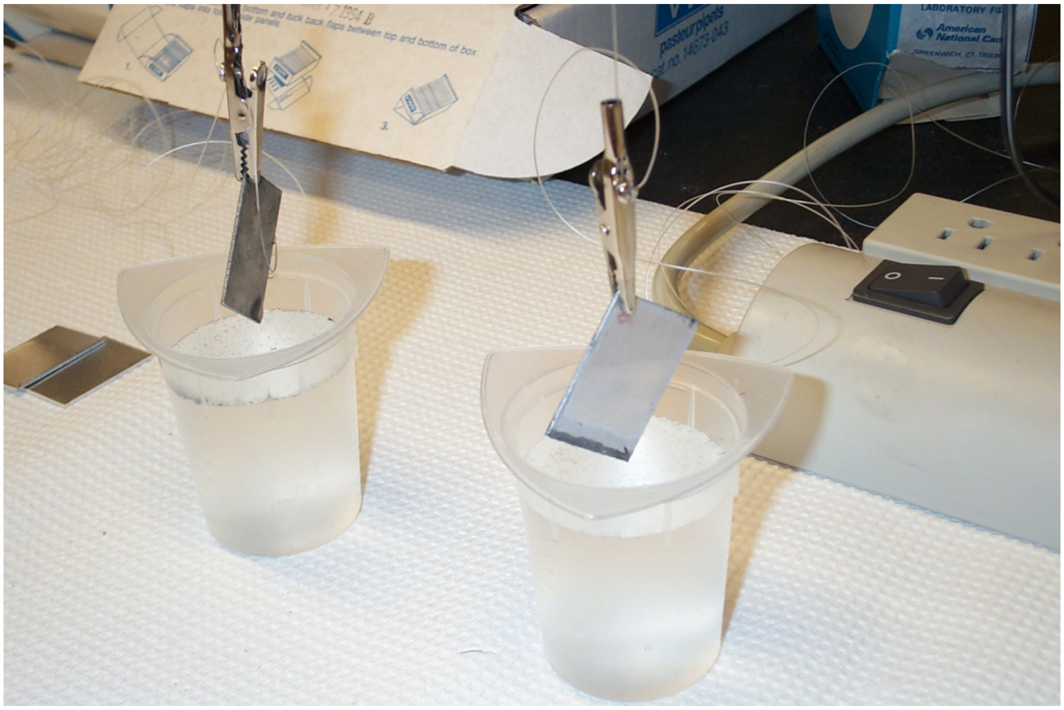

Figure 30: Specimens in Dipping Apparatus

Table 23: Procedure for Cleaning Anti-Freeze and Oil Contaminants

#	Procedure
1	Fill two 50 ml beakers with standard cleaning solution
3	Attach 1 of each type of soiled specimen to the dipping apparatus
4	Run dipping apparatus for 5 mins. at 20 $\pm$ 1 cycles/min.
5	Replace beakers of cleaning solution with distilled water
6	Run dipping apparatus for 60 $\pm$ 1 s to rinse specimens
7	Remove specimens
8	Note any visible changes in contamination level
9	Set aside and return to step 1
10	Repeat steps 1-6 until all specimens have been cleaned or enough cleaned specimens for an oven batch have been generated
11	Oven dry specimens for 1 hr. at 65 $\pm$ 2 C
12	Remove specimens and allow to air cool
13	Weigh and record specimen mass, zeroing the scale and changing weigh paper as needed.

4.3 Contamination Resistance and Cleaning Burden Data

Table 24-Table 31 document contaminant and cleaning effectiveness data obtained by following the procedures enumerated in Section 4.2. These tables occur in four pairs. The pairs record the results for particulate (graphite), brine solution, motor oil

and anti-freeze contamination, respectively. The first of each pair contains data for uncoated specimens (i.e. Table 24) while the second contains data for specimens with self-cleaning surfaces (i.e. Table 25). Odd numbered specimens are uncoated while even numbered ones are coated.

Table 24: Graphite Contamination Experiment Results for Uncoated Specimens

Spec. #	Specimen Mass [g]	Soiled Specimen Mass [g]	Post-Cleaning Specimen Mass [g]	Applied Contaminant Mass [mg]	Post-Cleaning Contaminant Mass [mg]	Contaminant Proportion Removed [%]
1	3.1246	3.1273	3.1260	2.7	1.4	48%
3	3.1643	3.1701	3.1655	5.8	1.2	79%
5	3.1655	3.1674	3.1658	1.9	0.3	84%
7	3.1224	3.1265	3.1234	4.1	1.0	76%
9	3.2004	3.2024	3.2010	2.0	0.6	70%
11	3.0815	3.0831	3.0820	1.6	0.5	69%
13	3.1699	3.1725	3.1707	2.6	0.8	69%
15	3.1199	3.1294	3.1208	9.5	0.9	91%
17	3.1959	3.1989	3.1967	3.0	0.8	73%
19	3.1647	3.1679	3.1655	3.2	0.8	75%
21	3.1259	3.1288	3.1274	2.9	1.5	48%
23	3.1325	3.1344	3.1332	1.9	0.7	63%
25	3.1867	3.1876	3.1869	0.9	0.2	78%
27	3.1901	3.1906	3.1903	0.5	0.2	60%
29	3.1891	3.1898	3.1895	0.7	0.4	43%
31	3.1031	3.1059	3.1037	2.8	0.6	79%
33	3.1808	3.1812	3.1808	0.4	0.0	100%
35	3.1661	3.1721	3.1672	6.0	1.1	82%
37	3.2085	3.2092	3.2085	0.7	0.0	100%
39	3.2071	3.2082	3.2074	1.1	0.3	73%
41	3.1658	3.1712	3.1671	5.4	1.3	76%
43	3.1304	3.1386	3.1318	8.2	1.4	83%
45	3.1386	3.1418	3.1398	3.2	1.2	62%
47	3.1184	3.1219	3.1192	3.5	0.8	77%
49	3.1384	3.141	3.1395	2.6	1.1	58%
51	3.1346	3.1369	3.1357	2.3	1.1	52%
53	3.2373	3.2381	3.2375	0.8	0.2	75%
55	3.1768	3.1777	3.1773	0.9	0.5	44%
57	3.1294	3.1354	3.1308	6.0	1.4	77%
59	3.1234	3.1279	3.1243	4.5	0.9	80%

Figure 31: Specimens Contaminated with Graphite

Table 25: Graphite Contamination Results for Coated Specimens

Spec. #	Specimen Mass [g]	Soiled Specimen Mass [g]	Post-Cleaning Specimen Mass [g]	Applied Contaminant Mass [mg]	Post-Cleaning Contaminant Mass [mg]	Contaminant Proportion Removed [%]
2	3.1782	3.1791	3.1784	0.9	0.2	78%
4	3.0744	3.0753	3.0745	0.9	0.1	89%
6	3.1322	3.1329	3.1324	0.7	0.2	71%
8	3.1503	3.1519	3.1505	1.6	0.2	88%
10	3.1215	3.1224	3.1218	0.9	0.3	67%
12	3.1533	3.1533	3.1533	0.0	0.0	100%
14	3.1543	3.1549	3.1544	0.6	0.1	83%
16	3.1569	3.1575	3.1571	0.6	0.2	67%
18	3.0983	3.0986	3.0982	0.3	-0.1	133%
20	3.0848	3.0879	3.0849	3.1	0.1	97%
22	3.1074	3.1079	3.1076	0.5	0.2	60%
24	3.1507	3.1510	3.1507	0.3	0.0	100%
26	3.2223	3.2229	3.2222	0.6	-0.1	117%
28	3.2302	3.2306	3.2303	0.4	0.1	75%
30	3.1266	3.1272	3.1268	0.6	0.2	67%
32	3.1511	3.1514	3.1509	0.3	-0.2	167%
34	3.3052	3.3055	3.3051	0.3	-0.1	133%
36	3.0344	3.0348	3.0343	0.4	-0.1	125%
38	3.1563	3.1569	3.1564	0.6	0.1	83%
40	3.2114	3.2123	3.2117	0.9	0.3	67%

Table 25 Continued						
42	3.1135	3.1143	3.1139	0.8	0.4	50%
44	3.1296	3.1303	3.1297	0.7	0.1	86%
46	3.1637	3.1647	3.1641	1.0	0.4	60%
48	3.0932	3.0937	3.0934	0.5	0.2	60%
50	3.1722	3.1727	3.1726	0.5	0.4	20%
52	3.1575	3.1581	3.1576	0.6	0.1	83%
54	3.2075	3.2078	3.2076	0.3	0.1	67%
56	3.1368	3.1380	3.1368	1.2	0.0	100%
58	3.1318	3.1329	3.1320	1.1	0.2	82%
60	3.1220	3.1231	3.1222	1.1	0.2	82%

Graphite soiling took two forms. The first form consisted of a thin coat of graphite covering the entire specimen that one could detect by wiping the specimen with white tissue paper. Noticeable lumps and streaks of graphite constituted the second form of graphite soiling (See Figure 32). This latter form of contamination seemed particularly prevalent on uncoated specimens (See Figure 31).

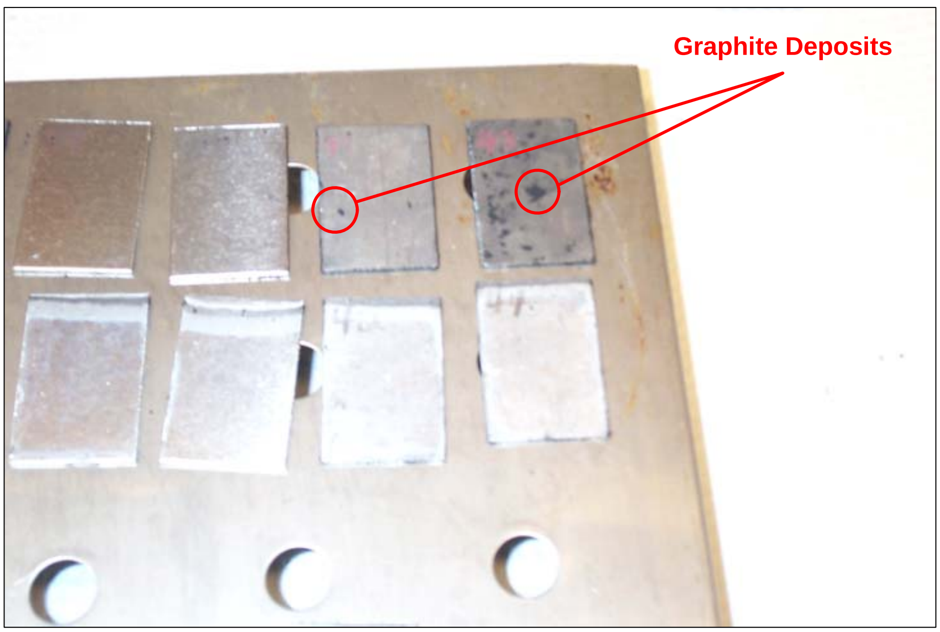

Figure 32: Specimens with Lump and Streak Graphite Deposits

Table 25 lists some negative post-cleaning contaminant masses. Though physically impossible, these measurements result from normal measurement variation, not a systematic error. Many coated specimens appeared clean following the distilled water wash. Since the scale used to measure mass has a manufacturer rated precision of ± 0.1 mg, it is quite possible that a clean specimen could appear to weigh 0.1 mg less. The Mettler Toledo scale sometimes changed readings by 0.1-0.2 mg if the sample remained on its stage for a few minutes. These sources of machine and human error appear to add ± 0.2 or ± 0.3 mg of random error to these measurements, making readings as low as -0.3 mg acceptable.

Table 26: 0.90 M NaCl Brine Solution Contamination Results for Uncoated Specimens

Spec. #	Specimen Mass [g]	Soiled Specimen Mass [g]	Post-Cleaning Specimen Mass [g]	Applied Contaminant Mass [mg]	Post-Cleaning Contaminant Mass [mg]	Contaminant Proportion Removed [%]
241	3.1961	3.2032	3.1960	7.1	-0.1	101%
243	3.1257	3.2041	3.1259	78.4	0.2	100%
245	3.1880	3.2072	3.1886	19.2	0.6	97%
247	3.1503	3.1624	3.1504	12.1	0.1	99%
249	3.1030	3.1822	3.1030	79.2	0.0	100%
251	3.1163	3.1730	3.1165	56.7	0.2	100%
253	3.1612	3.2284	3.1612	67.2	0.0	100%
255	3.1888	3.2658	3.1892	77.0	0.4	99%
257	3.1466	3.1526	3.1469	6.0	0.3	95%
259	3.1486	3.1565	3.1486	7.9	0.0	100%
261	3.1915	3.1959	3.1918	4.4	0.3	93%
263	3.1440	3.1472	3.1403	3.2	-3.7	216%
265	3.1047	3.1082	3.1047	3.5	0.0	100%
267	3.1468	3.2206	3.1468	73.8	0.0	100%
269	3.1329	3.2139	3.1331	81.0	0.2	100%
271	3.1112	3.1125	3.1113	1.3	0.1	92%
273	3.1622	3.2418	3.1622	79.6	0.0	100%
275	3.1816	3.2597	3.1816	78.1	0.0	100%
277	3.1455	3.2310	3.1454	85.5	-0.1	100%
279	3.1392	3.2167	3.1392	77.5	0.0	100%
281	3.1541	3.2302	3.1541	76.1	0.0	100%
283	3.1954	3.2717	3.1957	76.3	0.3	100%
285	3.0891	3.1665	3.0894	77.4	0.3	100%
287	3.1181	3.1973	3.1182	79.2	0.1	100%
289	3.0652	3.1471	3.0655	81.9	0.3	100%
291	3.1755	3.2613	3.1758	85.8	0.3	100%
293	3.1272	3.2079	3.1273	80.7	0.1	100%
295	3.1001	3.1790	3.1002	78.9	0.1	100%
297	3.1985	3.2738	3.1987	75.3	0.2	100%
299	3.1242	3.2030	3.1244	78.8	0.2	100%

Table 27: 0.90 M NaCl Brine Solution Contamination Results for Coated Specimens

Spec. #	Specimen Mass [g]	Soiled Specimen Mass [g]	Post-Cleaning Specimen Mass [g]	Applied Contaminant Mass [mg]	Post-Cleaning Contaminant Mass [mg]	Contaminant Proportion Removed [%]
242	3.1050	3.1301	3.1053	25.1	0.3	99%
244	3.1930	3.2037	3.1931	10.7	0.1	99%
246	3.1918	3.1962	3.1918	4.4	0.0	100%
248	3.1920	3.1975	3.1925	5.5	0.5	91%
250	3.1450	3.1465	3.1449	1.5	-0.1	107%
252	3.1350	3.1383	3.1349	3.3	-0.1	103%
254	3.1195	3.1419	3.1196	22.4	0.1	100%
256	3.2141	3.2244	3.2139	10.3	-0.2	102%
258	3.1645	3.1740	3.1647	9.5	0.2	98%
260	3.1590	3.1606	3.1590	1.6	0.0	100%
262	3.1723	3.1732	3.1722	0.9	-0.1	111%
264	3.1515	3.1535	3.1516	2.0	0.1	95%
266	3.0918	3.0965	3.0917	4.7	-0.1	102%
268	3.1152	3.1194	3.1152	4.2	0.0	100%
270	3.1248	3.1373	3.1247	12.5	-0.1	101%
272	3.1803	3.1824	3.1798	2.1	-0.5	124%
274	3.1232	3.1236	3.1230	0.4	-0.2	150%
276	3.1334	3.1627	3.1334	29.3	0.0	100%
278	3.1425	3.1487	3.1423	6.2	-0.2	103%
280	3.1421	3.1428	3.1419	0.7	-0.2	129%
282	3.2144	3.2351	3.2145	20.7	0.1	100%
284	3.1831	3.1836	3.1832	0.5	0.1	80%
286	3.1734	3.1734	3.1732	0.0	-0.2	100%
288	3.1084	3.1370	3.1084	28.6	0.0	100%
290	3.1912	3.2079	3.1916	16.7	0.4	98%
292	3.2060	3.2123	3.2059	6.3	-0.1	102%
294	3.1646	3.1684	3.1645	3.8	-0.1	103%
296	3.1352	3.1539	3.1353	18.7	0.1	99%
298	3.0659	3.0686	3.0659	2.7	0.0	100%
300	3.1273	3.1274	3.1274	0.1	0.1	0%

Brine droplet contact angle and stability varied by surface. Brine on uncoated surfaces formed stable droplets with acute contact angles (See Figure 33). The full 1.5 ml charge of brine solution remained on the specimens in many cases. However, some droplets in the first batch of 15 uncoated specimens were destabilized during transport to the drying oven. Lower contamination levels for specimens 241 and 257-265 are partially attributable to this handling induced droplet loss. Droplets on coated surfaces displayed obtuse (phobic) contact angles and proved highly unstable, often rolling off specimens during application. Remaining droplets were smaller than those on uncoated specimens and tended to adhere to coating defects.

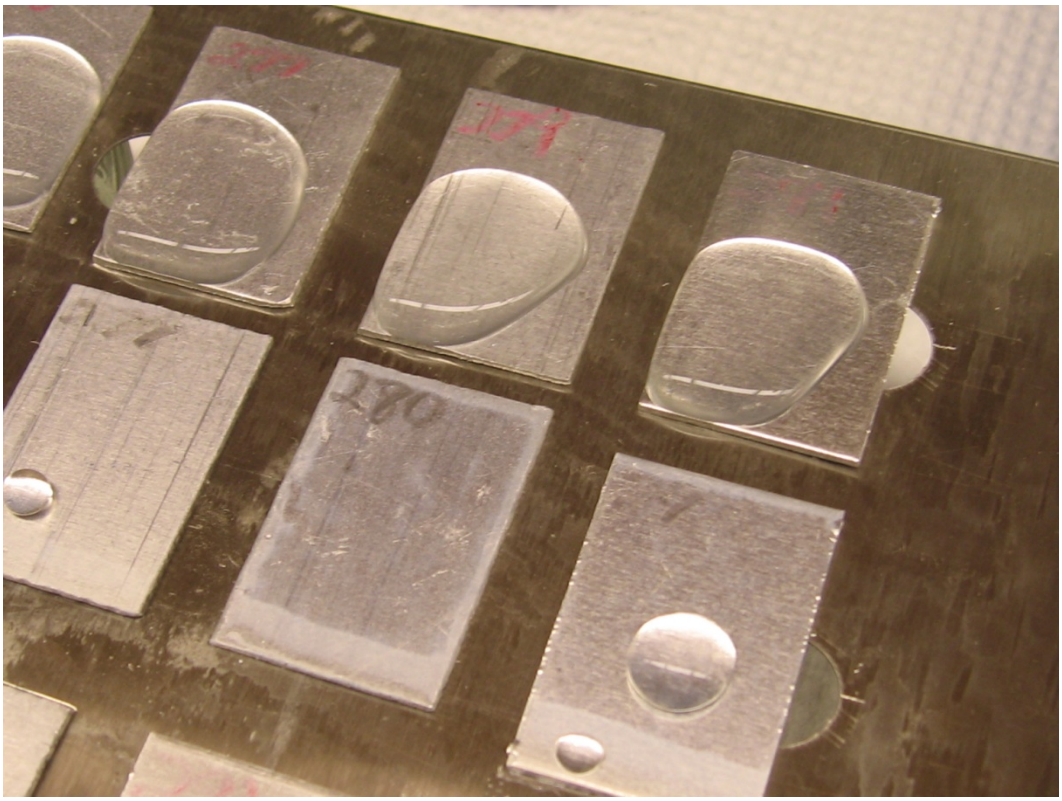

Figure 33: Specimens Contaminated with 0.90 M Brine

Specimens 263 and 272 fall beyond the established bounds of measurement error (See Table 26 and Table 27). At -3.7 mg, Specimen 263 is likely the result of a transcription error that occurred when it was first weighed. Though presented for the sake of completeness, neither specimen contributed to statistical calculations.

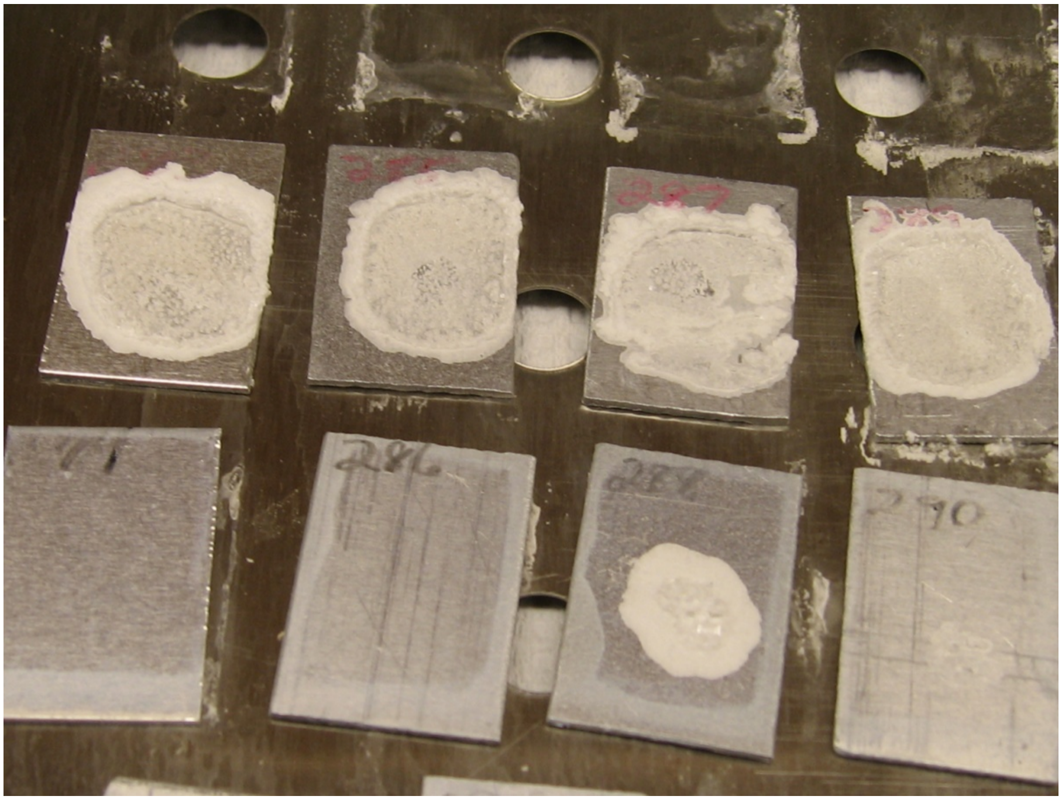

Figure 34: Salt Deposits Left on Brine Contaminated Specimens after Drying

Table 28: SAE 10W Motor Oil Contamination Results for Uncoated Specimens

Spec. #	Specimen Mass [g]	Soiled Specimen Mass [g]	Post-Cleaning Specimen Mass [g]	Applied Contaminant Mass [mg]	Post-Cleaning Contaminant Mass [mg]	Contaminant Proportion Removed [%]
181	3.1389	3.2157	3.1681	76.8	29.2	62%
183	3.2860	3.4180	3.3180	132.0	32.0	76%
185	3.1747	3.2698	3.2015	95.1	26.8	72%
187	3.1361	3.2245	3.1564	88.4	20.3	77%
189	3.1606	3.3323	3.1929	171.7	32.3	81%
191	3.1898	3.2808	3.2209	91.0	31.1	66%
193	3.1697	3.3040	3.2007	134.3	31.0	77%
195	3.1201	3.2488	3.1420	128.7	21.9	83%
197	3.1122	3.2210	3.1406	108.8	28.4	74%
199	3.1846	3.2599	3.2030	75.3	18.4	76%
201	3.1622	3.3671	3.1968	204.9	34.6	83%
203	3.1324	3.2545	3.1667	122.1	34.3	72%
205	3.1247	3.2182	3.1404	93.5	15.7	83%
207	3.2026	3.3945	3.2453	191.9	42.7	78%
209	3.1448	3.2261	3.1650	81.3	20.2	75%
211	3.1397	3.2395	3.1622	99.8	22.5	77%
213	3.1832	3.3281	3.2109	144.9	27.7	81%
215	3.1448	3.2963	3.1895	151.5	44.7	70%
217	3.1109	3.2235	3.1427	112.6	31.8	72%

Table 28 continued						
219	3.1478	3.2655	3.1750	117.7	27.2	77%
221	3.1357	3.2257	3.1606	90.0	24.9	72%
223	3.1256	3.2423	3.1499	116.7	24.3	79%
225	3.1300	3.2150	3.1568	85.0	26.8	68%
227	3.0797	3.1941	3.1036	114.4	23.9	79%
229	3.1243	3.2167	3.1519	92.4	27.6	70%
231	3.1096	3.2420	3.1378	132.4	28.2	79%
233	3.1502	3.3342	3.1874	184.0	37.2	80%
235	3.1298	3.2505	3.1648	120.7	35.0	71%
237	3.0548	3.1787	3.0817	123.9	26.9	78%
239	3.1431	3.1835	3.1557	40.4	12.6	69%

Table 29: SAE 10W Motor Oil Contamination Results for Coated Specimens

Spec. #	Specimen Mass [g]	Soiled Specimen Mass [g]	Post-Cleaning Specimen Mass [g]	Applied Contaminant Mass [mg]	Post-Cleaning Contaminant Mass [mg]	Contaminant Proportion Removed [%]
182	3.1030	3.1835	3.1346	80.5	31.6	61%
184	3.2149	3.2850	3.2423	70.1	27.4	61%
186	3.1116	3.2036	3.1461	92.0	34.5	62%
188	3.1273	3.2344	3.1626	107.1	35.3	67%
190	3.1762	3.2896	3.2142	113.4	38.0	66%
192	3.2100	3.3487	3.2562	138.7	46.2	67%
194	3.1304	3.2759	3.1752	145.5	44.8	69%
196	3.1350	3.2087	3.1638	73.7	28.8	61%
198	3.1193	3.2787	3.1597	159.4	40.4	75%
200	3.1296	3.2689	3.1779	139.3	48.3	65%
202	3.1972	3.2714	3.2266	74.2	29.4	60%
204	3.1034	3.2269	3.1435	123.5	40.1	68%
206	3.1149	3.2322	3.1518	117.3	36.9	69%
208	3.2097	3.3350	3.2444	125.3	34.7	72%
210	3.1520	3.3274	3.1873	175.4	35.3	80%
212	3.1488	3.2617	3.1713	112.9	22.5	80%
214	3.1580	3.3325	3.1960	174.5	38.0	78%
216	3.1362	3.2652	3.1822	129.0	46.0	64%
218	3.1106	3.2568	3.1524	146.2	41.8	71%
220	3.0835	3.1140	3.1142	30.5	30.7	-1%
222	3.1538	3.2756	3.1921	121.8	38.3	69%
224	3.1232	3.2056	3.1597	82.4	36.5	56%
226	3.1474	3.2534	3.1837	106.0	36.3	66%
228	3.1695	3.2794	3.1960	109.9	26.5	76%
230	3.1402	3.2716	3.1729	131.4	32.7	75%
232	3.1517	3.3432	3.1925	191.5	40.8	79%
234	3.2192	3.2882	3.2439	69.0	24.7	64%
236	3.1621	3.2505	3.1881	88.4	26.0	71%
238	3.0963	3.1974	3.1275	101.1	31.2	69%
240	3.1328	3.2415	3.1653	108.7	32.5	70%

As expected, motor oil wet both coated and uncoated surfaces (See Figure 35). Oil residue adhered to trays, weigh paper and other surfaces encountered by the specimens. Contaminant losses to these surfaces as well as the cleaning procedure contributed to observed contamination reduction on all specimens.

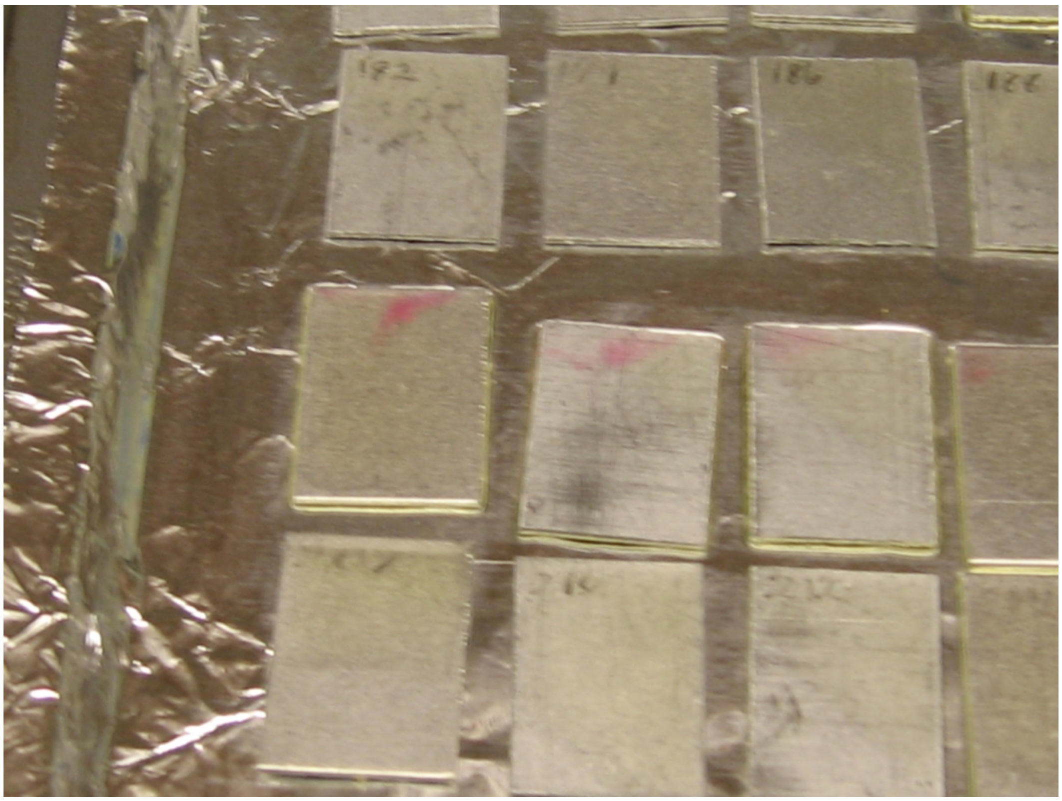

Figure 35: Motor Oil Contaminated Specimens

Table 30: Anti-Freeze Contamination Results for Uncoated Specimens

Spec. #	Specimen Mass [g]	Soiled Specimen Mass [g]	Post-Cleaning Specimen Mass [g]	Applied Contaminant Mass [mg]	Post-Cleaning Contaminant Mass [mg]	Contaminant Proportion Removed [%]
121	3.1053	3.1218	3.1053	16.5	0.0	100%
123	3.1774	3.1788	3.1774	1.4	0.0	100%
125	3.1913	3.2015	3.1906	10.2	-0.7	107%
127	3.2164	3.2246	3.216	8.2	-0.4	105%
129	3.099	3.1037	3.099	4.7	0.0	100%
131	3.1053	3.1123	3.1051	7.0	-0.2	103%
133	3.1958	3.1818	3.1958	-14.0	Error	Error
135	3.1347	3.1505	3.1344	15.8	-0.3	102%
137	3.0729	3.0816	3.0727	8.7	-0.2	102%
139	3.1638	3.1718	3.1635	8.0	-0.3	104%

Table 30 continued						
141	3.0934	3.1049	3.0933	11.5	-0.1	101%
143	3.1531	3.1649	3.1531	11.8	0.0	100%
145	3.1628	3.1679	3.1628	5.1	0.0	100%
147	3.1525	3.1629	3.1533	10.4	0.8	92%
149	3.2033	3.2239	3.2036	20.6	0.3	99%
151	3.1393	3.1463	3.1394	7.0	0.1	99%
153	3.1443	3.1475	3.1442	3.2	-0.1	103%
155	3.1564	3.1724	3.1563	16.0	-0.1	101%
157	3.2219	3.2328	3.2221	10.9	0.2	98%
159	3.1385	3.1491	3.1387	10.6	0.2	98%
161	3.1318	3.1472	3.1317	15.4	-0.1	101%
163	3.2002	3.2043	3.2001	4.1	-0.1	102%
165	3.1062	3.1212	3.1061	15.0	-0.1	101%
167	3.1795	3.1838	3.1795	4.3	0.0	100%
169	3.2738	3.2759	3.2737	2.1	-0.1	105%
171	3.1297	3.1458	3.1296	16.1	-0.1	101%
173	3.1846	3.1955	3.1845	10.9	-0.1	101%
175	3.1651	3.1833	3.1650	18.2	-0.1	101%
177	3.2143	3.2188	3.2143	4.5	0.0	100%
179	3.1261	3.1331	3.1259	7.0	-0.2	103%

Table 31: Anti-Freeze Contamination Results for Coated Specimens

Spec. #	Specimen Mass [g]	Soiled Specimen Mass [g]	Post-Cleaning Specimen Mass [g]	Applied Contaminant Mass [mg]	Post-Cleaning Contaminant Mass [mg]	Contaminant Proportion Removed [%]
122	3.0725	3.0869	3.0721	14.4	-0.4	103%
124	3.1745	3.1906	3.1744	16.1	-0.1	101%
126	3.2897	3.3033	3.2894	13.6	-0.3	102%
128	3.2171	3.2273	3.2169	10.2	-0.2	102%
130	3.1457	3.1587	3.1454	13.0	-0.3	102%
132	3.1455	3.1643	3.1456	18.8	0.1	99%
134	3.1913	3.2055	3.1911	14.2	-0.2	101%
136	3.1478	3.1626	3.1478	14.8	0.0	100%
138	3.1781	3.1975	3.1780	19.4	-0.1	101%
140	3.1171	3.1332	3.1169	16.1	-0.2	101%
142	3.2160	3.2343	3.2160	18.3	0.0	100%
144	3.1954	3.2103	3.1951	14.9	-0.3	102%
146	3.1010	3.1112	3.1005	10.2	-0.5	105%
148	3.1925	3.2071	3.1921	14.6	-0.4	103%
150	3.1625	3.1790	3.1624	16.5	-0.1	101%
152	3.2229	3.2397	3.2226	16.8	-0.3	102%
154	3.1639	3.1898	3.1637	25.9	-0.2	101%
156	3.1326	3.1507	3.1324	18.1	-0.2	101%
158	3.2201	3.2355	3.2200	15.4	-0.1	101%
160	3.1783	3.1956	3.1782	17.3	-0.1	101%
162	3.1615	3.1779	3.1614	16.4	-0.1	101%
164	3.1755	3.1935	3.1754	18.0	-0.1	101%
166	3.2021	3.2187	3.2023	16.6	0.2	99%

Table 31 continued						
168	3.2427	3.2661	3.2429	23.4	0.2	99%
170	3.1407	3.1518	3.1406	11.1	-0.1	101%
172	3.1279	3.1485	3.1280	20.6	0.1	100%
174	3.1343	3.1560	3.1344	21.7	0.1	100%
176	3.1556	3.1687	3.1556	13.1	0.0	100%
178	3.1393	3.1673	3.1393	28.0	0.0	100%
180	3.1042	3.1153	3.1041	11.1	-0.1	101%

Though an aqueous solution, anti-freeze wet coated and uncoated surfaces. A noticeable film covered all specimens after contamination. Washing specimens in the detergent solution appeared to completely remove contamination. Interestingly, anti-freeze or a combination of anti-freeze and detergent partially removed the self-cleaning coating on a number of specimens.

Specimens 122, 125, 133, 146 and 148 in Table 30 and Table 31 fall beyond the -0.3 mg limit for acceptable variation. However, coating loss slightly reduces coating mass and could bias mass measurements downward. Therefore, with the exceptions of specimens 125 and 133, these data were used in statistical calculations.

4.4 Contamination Resistance and Burden Reduction

Statistical analysis of data in Section 4.3 reveals the significance, magnitude and extent of contamination resistance and cleaning success imparted by the applied coating. The presence of approximately 30 data points for each comparison between coated and uncoated surfaces allows estimation of significance using two-tailed t-tests (Hayter 2002). Means for contaminant mass after soiling and percent contaminant removed quantify magnitude. Reviewing significance and magnitude for four different contaminants provides insight into the extent of the self-cleaning surface's capabilities. Table 32 summarizes this data for each contaminant and experiment.

Table 32: Statistical Summary of Contamination Resistance and Cleaning Experiments

			Mean Contam.	Stan. Dev.	p-value (two-tail t-test)
Graphite	**Contamination Resistance**	**Coated (N=30)**	0.7 mg	0.6 mg	6.5E-06
		Uncoated (N=30)	3.1 mg	2.3 mg	
	Cleaning	**Coated (N=30)**	85%	29%	0.025
		Uncoated (N=30)	71%	15%	
Brine (0.90 M)	**Contamination Resistance**	**Coated (N=29)**	8.7 mg	9.1	4.6E-9
		Uncoated (N=29)	58.1 mg	32.2	
	Cleaning	**Coated (N=29)**	99%	22%	.969
		Uncoated (N=29)	99%	2%	
Motor Oil	**Contamination Resistance**	**Coated (N=30)**	114.6 mg	35.9	0.7681
		Uncoated (N=30)	117.4 mg	36.9	
	Cleaning	**Coated (N=30)**	66%	14%	0.0026
		Uncoated (N=30)	75%	5%	
Anti-Freeze	**Contamination Resistance**	**Coated (N=30)**	16.6 mg	4.3 mg	1.9 E-6
		Uncoated (N=28)	9.8 mg	5.3 mg	
	Cleaning	**Coated (N=30)**	101%	1.3%	0.6658
		Uncoated (N=28)	101%	2.4%	

Results from the graphite contamination experiments fully support the assertion that micro/nano-rough surfaces phobic to contaminant carriers reduce use phase cleaning burdens. Surfaces formed by TegoTop® on aluminum provide highly significant resistance to contamination (p-value = 6.5E-6) and appear to significantly improve cleaning (p-value = 0.025). A surface coated with Tegotop® retains four times less contaminant (mean = 0.7 mg) than an uncoated surface (mean = 3.1 mg). Washing with distilled water removes an average of 85% of the contaminants on a coated surface to 71% on an uncoated one. These results suggest that the title of "self-cleaning surface" is a misnomer. In the case of particulates, the primary advantage comes from its ability to resist contamination. Nonetheless, differences in contamination and ease of cleaning imply that such surfaces would require fewer cleanings and less effort when cleaned.

Brine solution contamination experiments yielded mixed results. Coated surfaces proved highly resistant to contamination, displaying a mean contamination mass (8.7 mg) seven times less than uncoated surfaces (58.1 mg) with a highly significant p-value of 4.6E-9. However, they displayed equally high cleaning capacities of 99%, and with a p-value of .969, they were statistically indistinguishable. These results underscore the observation that resistance to soiling is, perhaps, the primary advantage of micro/nano-rough phobic surfaces. While advantages in cleaning did not surface during the brine experiment, it is worth noting that contaminant removal remained high and that surface roughness did not hamper removal of crystallized contaminants. Overall, superior resistance to contamination and at least equal ease of cleaning also suggest that these types of surfaces reduce cleaning burdens.

Contamination with fresh motor oil generated results in contrast to those from the particulate and brine experiments. Coated surfaces retained slightly less oil (mean = 114.6 mg) after contamination than uncoated ones (mean = 117.4 mg), but this difference proved insignificant (p-value = 0.7681). More importantly, coated surfaces fared worse during cleaning than uncoated ones. Coated surfaces shed 66% of their oil while uncoated ones shed 75%. It is likely that infiltration of the coating's surface texture explains this significant difference (p-value = .0026) in cleaning performance. Hydrophobic surfaces tend not to be oleophobic. When oily compounds come in contact with micro/nano-rough hydrophobic surfaces, they can wet the surface and fill micro and nano-scale structures, making removal more difficult. This result does not so much disprove the contention that self-cleaning surfaces reduce cleaning burdens as illustrate the importance of contaminant carrier phobicity.

The anti-freeze experiments produced a surprising outcome. Coated surfaces retained more than 1.5 times as much contaminant as uncoated ones, but both sets of specimens exhibited the same level of cleaning performance. Ethylene glycol's solubility in water coupled with coating destruction explains equivalent cleaning performance. As the coating disintegrated, coated specimens began to revert to their uncoated states and behaviors.

The initial contamination outcome is surprising because anti-freeze is an aqueous solution, and since the coated surface is hydrophobic, one might expect non-wetting behavior similar to that observed for brine. However, anti-freeze contains ethylene glycol. This miscible organic compound acts as a surfactant which lowers the surface tension (γ_{lf}) of water. A form of Young's Equation for contact angles (θ_c) reveals the impact of reduced surface tension on wetting behavior (See Equation 5).

$$\theta_c = \cos^{-1}\left(\frac{\gamma_{sf} - \gamma_{sl}}{\gamma_{lf}}\right) \tag{5}$$

As surface tension falls, the ratio of surface energy difference ($\gamma_{sf} - \gamma_{sl}$) to surface tension increases. An increase in this ratio translates into a decrease in contact angle. Wenzel's equation further explains the observed behavior for micro/nano-rough surfaces (Wenzel 1936).

$$\cos\theta_R = r(\cos\theta_c) \qquad (6)$$

His equation relates contact angles between the same liquids and solids observed on smooth surfaces with those observed on rough surfaces (θ_R). A roughness factor (r) relates the two. The roughness factor is the ratio of real surface area to flat or projected surface area, and therefore, it always exceeds one for rough surfaces. The form of the equation insures that roughness drives contact angles away from 90^0; so, a droplet made hydrophilic by a surfactant becomes even more hydrophilic when placed on a rough surface. Anti-freeze failed to bead because the ethylene glycol reduced its contact angle, and surface roughness enhanced its wetting. This combined effect likely explains the excess anti-freeze retained on coated surfaces following contamination.

The overall result of the anti-freeze experiment underscores the need to match self-cleaning coatings with their environment. Tegotop® mimics the coating found on a lotus leaf, and consequently, it performs well against types of contaminants found in the lotus' environment such as particulates and ionic, aqueous solutions. It fails against oils and solutions loaded with surfactants, contaminants usually not available in a lotus' environment.

4.5 The Value of Micro / Nano Structured Phobic Surfaces

Experiments in Chapter 4 support the usefulness of the biologically derived guideline stated at the outset. The results support the contention that components and products embodying this guideline will consume fewer cleaning resources during different parts of their life cycles, thus reducing associated environmental burdens. The results also help define the guideline's boundaries and even suggest potential applications.

The tested coating strongly resists contamination by particulates and ionic aqueous solutions. For these contaminants, it is equally or more easily cleaned than untreated aluminum surfaces. Benefits often proved sizeable; coated surfaces resisted contamination 4-7 times better than uncoated ones. Surfaces with multiple times less contamination would require fewer cleanings during their useful lives. Therefore, such data argue in favor of the presented guideline's environmental value.

However, surfaces with the micro/nano-rough, hydrophobic coating demonstrated equivalent or worse performance against oil and surfactant laden contaminants. These contaminants wet coated surfaces, and one appeared to damage coated surfaces. Since the surface was not phobic to these soiling agents, its small scale roughness became a cleaning liability, enhancing wetting and capturing contaminants. Such outcomes illustrate the importance of fully applying the guideline by matching surface chemistry to expected environments. Had an oleophobic coating been used in the oil experiment, the results likely would have been different.

Looking beyond cleaning, the response of the coating to wetting contaminants suggests some rheological or tribological applications. The surfaces tended to trap fluids when they wet. The results presented in this Chapter show that these surfaces can preferentially hold lubricants and, therefore, might provide a viable means of achieving preferential lubrication. Building a three-dimensional microstructure on a part's surface that one could impregnate with lubricant or coolant represents a variation on this theme.

Taken together, Chapter 4's findings imply that modulating adhesion using contaminant carrier phobic mico/nano-rough surfaces will lead to environmental benefits. The negative findings primarily show that one must pay attention to the operating environment in which one employs these surfaces to ensure the implied benefits. Stepping away from the specifics of testing this one guideline, this qualified success lends a measure of support to the dissertation's overarching contention that one can derive and employ bio-inspired engineering guidance.

CHAPTER 5: ON THE QUESTION OF SUSTAINABLE ENERGY CONSUMPTION

Chapter 5 continues the evaluation process for the biological principles extracted and translated in Chapter 3. At the product / organism scale, Chapter 5 explores the predictive environmental capability of the design guideline:

Limit the rate of energy consumption per unit mass.

Two reasonable interpretations of this guideline exist. The first views the specific consumption limit as a simple product level measure of environmental performance. Returning to the metabolic roots of the guideline, the second interpretation considers it a limit on each human's extended metabolism, the total energy consumption rate of an average person and his technology during daily life. Chapter 5 investigates the predictive capability of both interpretations.

Predictive capability determination is a three step process. For a set of analyzed objects or citizens, one first estimates the mass specific energy consumption rate. Then, one uses established techniques to estimate environmental impact. Finally, one compares the two sets to determine whether the approaches yield the same rank ordering of impacts and identify the same thresholds.

Section 5.1 establishes the importance of specific energy consumption rates (SECR) by estimating SECR values for a number of common products. Section 5.2 evaluates SECR's predictive capacity in a product design context by generating and comparing design variants for a log splitter using SECR and Eco-indicator 99. Extended metabolism exploration occurs in Section 5.3. National trends in ecological footprint analysis are compared with trends in SECR for citizens of selected countries. Section 5.4 reflects upon the predictive capability of the explored guideline in light of the preceding analyses.

5.1 Importance of Specific Energy Consumption Rates

The importance of a metric depends on its ability to differentiate objects and identify qualitatively different states for said objects. In the case of SECR, one needs to establish that different objects possess different SECR values and that some objects fall on different sides of the metabolic bounds found in nature. This section satisfies both prerequisites for further analysis by estimating the SECR of selected white goods and vehicles. Those specifically interested in SECR relationships of white goods and vehicles should consult the publication by Reap and Bras (Reap, et al. 2008).

5.1.1 Specific Energy Consumption Rates for Microwave Ovens

Table 33 contains data needed to estimate the specific energy consumption rate for a number of microwave ovens. Manufacturers' and retailers' websites[7] maintain this data. To compare microwave ovens to organisms, name plate power ratings were divided by either net or shipping weight to calculate specific energy consumption rates (SECR).

[7]http://products.geappliances.com/ApplProducts/Dispatcher?REQUEST=SPECPAGE&SKU=JE1590SH&SITEID=GEA&TABID=2

Table 33: Specific Energy Consumption Rates and Related Data for Selected Microwave Ovens

Manufac.	Model	Size [cm^3]	Mass [kg]	Power Rating [W]	Operational SECR [W/kg]
GE	JE1590SH	42	23.6	1500	63.6
GE	JES1290SK	34	20.4	1500	73.5
GE	JES2251SJ	62	15.4	1200	77.8
GE	JE1860SH	51	19.5	1550	79.5
Panasonic	NNH765WF	45	12.2	1250	102.1
Panasonic	NNT995SF	62	18.1	1250	68.9
Panasonic	NNSD696S	34	11.8	1300	110.2
Panasonic	NNS505BF	31	10.4	1200	115.0
SHARP	R1214	42	24.9	1100	44.1
SHARP	R2130JS	59	21.3	1200	56.3
SHARP	R1514	42	24.9	1000	40.1
SHARP	R530ES	57	18.6	1200	64.5

5.1.2 Specific Energy Consumption Rates for Air Conditioners

Table 34 contains data needed to estimate the specific energy consumption rate for selected window / wall mounted air conditioners. All data were gleaned from retailers' websites[8]. Specific energy consumption rates are determined by first estimating power consumption based on each air conditioner's cooling capacity Q_{cool} and energy efficiency ratio (EER) (See Eqn. 7). EER is the ratio of cooling capacity [BTU/hr] to power consumption [W]. Dividing air conditioner mass by power consumption produces operational SECR.

$$P_{AC} = \frac{Q_{cool}}{EER} \tag{7}$$

[8] see, for example, http://www.airconditioner.com/ROOM_AIR_CONDITIONERS

Table 34: Specific Energy Consumption Rates and Related Data for Selected Window / Wall Mounted Air Conditioners

Manufac.	**Model**	**Cooling Capacity** [kJ/hr]	**Mass** [kg]	**Power Consumption** [W]	**Operational SECR** [W/kg]
FRIGIDAIRE	FAA052N7A	5275	24.0	515	21.4
FRIGIDAIRE	FAX054P7A	5275	20.0	515	25.8
FRIGIDAIRE	FAA055N7A	5486	24.5	536	21.9
GOLDSTAR	LWA0510CL	5275	22.2	625	28.1
GOLDSTAR	LWA0510CT	5275	22.2	625	28.1
FRIEDRICH	ZQ05A10	5275	20.0	515	25.8
FRIEDRICH	KQ05J10	5592	34.5	589	17.1
EMERSON	5GC53	5381	29.5	567	19.2
EMERSON	6GC53	6330	31.8	600	18.9
GE	AKL05LA	5275	24.9	515	20.7

5.1.3 Specific Energy Consumption Rates for Computer Monitors

Table 35 contains data used to estimate the SECR for liquid crystal display (LCD) and cathode ray tube (CRT) computer monitors. Retailers' and manufacturers' websites maintain this data[9]. As with microwave ovens, power consumption rating divided by monitor mass yields operational SECR.

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[9] see http://www.superwarehouse.com/NEC_AccuSync_LCD72VX_White_17_LCD_Monitor/ASLCD72VX/ps/729644

Table 35: Specific Energy Consumption Rates and Related Data for Selected Computer Monitors

Manufac.	**Model**	**Type / Diagonal Length** [cm]	**Mass** [kg]	**Power Rating** [W]	**Operational SECR** [W/kg]
NEC	AccuSync ASLCD72VX	LCD / 43	4.8	36	7.5
NEC	MultiSync 70GX2	LCD / 43	4.6	30	6.5
NEC	AccuSync ASLCD72V-BK-T	LCD / 43	5.7	47	8.2
3M	Privacy Monitor 01-82110-00	LCD / 43	8.0	30	3.7
3M	MicroTouch ChassisTouch Black FPD 11-4942-129-00	LCD / 43	5.1	44	8.7
HP	s7540 Silver/Carbon	CRT / 41	4.6	20	4.4
HP	s7650 Silver/Carbon	CRT / 41	14.1	64	4.6
IBM	C117	CRT / 41	16.0	61	3.8
IBM	ThinkVision E74	CRT / 41	15.5	70	4.5
Philips	107E76/27	CRT / 43	15.5	68	4.4

5.1.4 Specific Energy Consumption Rates for Automobiles and Buses

Table 36 contains information used to calculate specific energy consumption rates for personal vehicles ranging in size from compact automobiles to pickup trucks while Table 37 contains similar information for buses. Mass, engine and fuel economy information contained in Table 37 was gleaned from three transit bus studies (O'Keefe, et al. 2002, Wayne, et al. 2004, Proc, et al. 2006). Curb weights (m_{curb}) serve as estimates for vehicle masses. Dividing engine power (P) by thermal efficiency yields energy consumption. Less efficient spark ignition engines used in the listed personal vehicles have a thermal efficiency of 0.25 (η_{SI}) while the more efficient compression ignition engines used by the buses merit an efficiency of 0.35 (η_{CI}) (Cengel, et al. 1998).

Specific energy consumption rate is a ratio of energy use per unit time to vehicle mass. Equation 8 combines these estimates and assumptions to determine operational specific rates of energy consumption for the listed personal vehicles (e_{pv}) while Equation 9 accomplishes the same task for buses (e_{bus}).

$$e_{pv} = \frac{P}{\eta_{SI} m_{curb}} \tag{8}$$

$$e_{bus} = \frac{P}{\eta_{CI} m_{curb}} \tag{9}$$

Table 36: Specific Energy Consumption Rates and Related Data for Selected Personal Vehicles

Manufac.	**Year**	**Vehicle**	**Fuel Consump.** [km/L]	**Curb Mass** [kg]	**Engine Power** [W]	**Operational SECR** [W/kg]
Toyota	2007	Prius	23.4	1330	82000	246.6
Toyota	2007	Yaris Sedan	15.5	1053	79044	300.3
Toyota	2007	Camry LE V6	11.3	1570	199848	509.2
Toyota	2007	Highlander 4-cyl.	10.6	1595	115583	289.9
Toyota	2007	Tundra 4x2 Reg. Cab V6	8.5	1785	175985	394.4
Daimler-Chrysler	2006	PT Cruiser	10.6	1427	111855	313.5
Daimler-Chrysler	2007	Sebring 2.4L	11.9	1491	129000	346.1
Daimler-Chrysler	2006	300	10.4	1684	141683	336.5
Daimler-Chrysler	2007	Aspen Limited 4x2	6.6	2207	175239	317.6
Daimler-Chrysler	2006	RAM 1500 ST Reg. Cab 4x4 SWB	6.8	2248	175239	311.8
GM	2007	Chevrolet Aveo	12.8	1153	76807	266.5
GM	2007	Chevrolet Cobalt 2.2L	11.9	1357	110363	325.3

Table 36 continued						
GM	2007	Chevrolet Monte Carlo	11.1	1570	157000	400.0
GM	2007	Chevrolet Equinox FWD	9.6	1664	137954	331.6
GM	2007	Chevrolet Silverado V6 Reg. Cab 2WD	7.9	1910	145411	304.5

Table 37: Specific Energy Consumption Rates and Related Data for Selected Transit Buses

Manufac.	**Year**	**Engine & Fuel**	**Fuel Consump.** [km/L]	**Curb Mass** [kg]	**Engine Power** [W]	**Operational SECR** [W/kg]
New Flyer	1996	DDC Diesel	1.65	13120	205000	44.6
New Flyer	1997	DDC Diesel	2.51	13438	205068	43.6
New Flyer	1998	Cummins Diesel-Hybrid	2.47	13839	205068	42.3
Nova Bus	1998	Cummins Diesel	1.63	13290	208796	44.9
Nova Bus	1999	RTS Diesel	1.48	14170	205000	41.3
Orion	2000	Cummins Diesel	1.87	13063	208796	45.7

5.1.5 Specific Energy Consumption Rates for Commercial Aircraft

Using publicly available data for aircraft mass, fuel capacity, range and cruise velocity found on the websites of Boeing[10] and Airbus[11], Table 38 estimates specific

[10] see, for example, http://www.boeing.com/commercial/737family/pf/pf_600tech.html

[11] see, for example, http://www.airbus.com/en/aircraftfamilies/a320/a318/specifications.html

energy consumption rates for commercial airliners using a few simple equations. Assuming an average jet fuel density (ρ_f) of 797 kg/m^3 (Peyton 1998), one estimates total mass by summing the mass of an empty aircraft (m_a) and fuel mass (m_{fuel}) (See Eqn. 10).

$$m_{total} = m_a + m_{fuel} \tag{10}$$

One can approximate average energy consumption rates (E_{avg}) using the lower heating value ($h_{LHV,af}$) of jet fuel (43.5 MJ/kg (Peyton 1998)), knowledge of each aircraft's maximum range ($r_{\max}$) and cruise velocity (v_c) (See Eqn. 11).

$$E_{avg} = \frac{m_{fuel} h_{LHV}}{\left(r_{\max} / v_c \right)} \tag{11}$$

Equation 11 divides total energy consumption for a flight by an estimate of flight time. Dividing energy consumption rate by aircraft mass yields a specific energy consumption rate (See Eqn. 12).

$$e_{avg} = \frac{E_{avg}}{\left(m_{total} \right)} \tag{12}$$

Table 38: Specific Energy Consumption Rates and Related Data for Selected Commercial Aircraft

Manufac.	**Aircraft**	**Empty Fueled Aircraft Mass** [kg]	**Max Range** [Mm]	**Cruise Velocity** [m/s]	**Operational SECR** [W/kg]
Boeing	737-600	57116	5.65	236	660
Boeing	737-700	58386	6.23	236	585
Boeing	737-800	62151	5.67	236	605
Boeing	747-400	340946	13.5	254	391
Boeing	747-400ER	326572	9.20	250	587
Boeing	747-400 Combi	346851	13.4	253	385
Boeing	767-200ER	132542	12.2	237	321

Table 38 continued					
Boeing	767-300ER	160754	11.3	237	413
Boeing	767-300 Freighter	158105	6.06	237	784
Boeing	777-200	227988	9.65	249	460
Boeing	777-300	292660	11.0	249	453
Airbus	A318	39300	5.95	248	877
Airbus	A321	48200	5.60	248	755
Airbus	A330-200	119600	12.5	261	842
Airbus	A340-500	170900	16.1	261	730

5.1.6 Differentiating Products with SECR

Figure 36 plots SECR data calculated in Sections 5.1.1-5.1.5 alongside specific metabolic rates for organisms. The plot shows that product variants in each class possess noticeably different SECR values. One also sees that different classes of products fall on both sides of the upper bound (40 W/kg) on field metabolic range. In short, it illustrates that one can differentiate products using SECR.

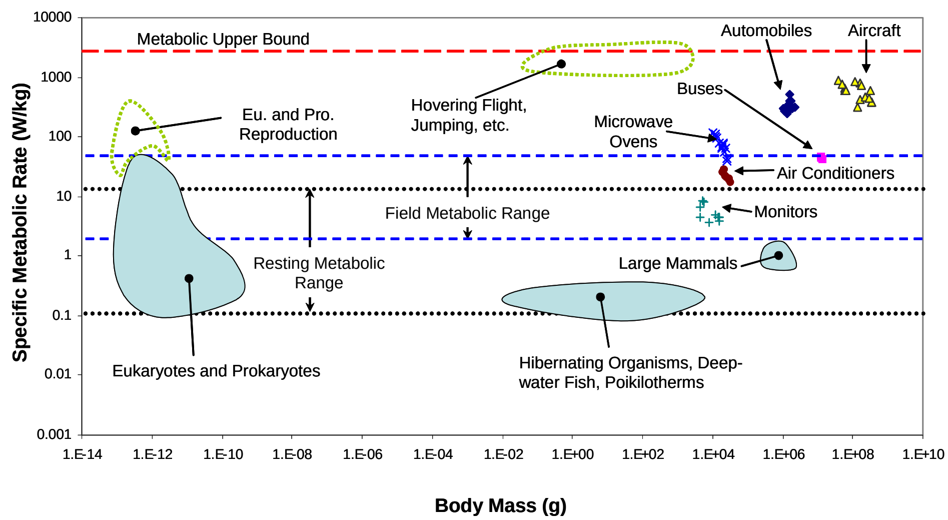


Figure 36: Specific Energy Consumption Rates for Organisms and Devices (adapted from (Makarieva, et al. 2005b, a))

5.2 Correlating Eco-Impact and SECR

Having established SECR's ability to differentiate among products and product variants, one can examine its ability to predict environmental impact. Basic design of a mechanical system serves as a means of exploring the predictive capacity of SECR as an environmental indicator. Log-splitters designed with SECR as an environmental goal are compared with those using the Eco-Indicator 99 (EI-99) metric. The test of SECR's predictive ability is whether it can drive the design toward the same configuration as one based on EI-99.

5.2.1 Modeling a Log Splitter

Common forestry tools, log-splitters cleave cylindrical tree trunk or branch sections in half using a wedge and a mechanism for applying force (See Figure 37). A screw drive or hydraulic ram typically delivers the force, and one can power either with an electric motor or gasoline engine. Gasoline powered hydraulic systems are more common.

Figure 37: Example of a hydraulic log-splitter powered by a gasoline engine

In addition to force, operators typically desire rapid splitting, portability, minimum cost and the ability to accommodate large logs. This work adds an environmental goal to the list of performance objectives. It represents environmental impact using two different types of metrics.

Goal	Design Representation
Deliver splitting force	Maximize ram force
Accommodate large logs	Maximize stroke length
Low cost	Minimize product cost
Portable	Minimize mass
Rapid splitting	Minimize cycle time
Low environmental impact	Minimize EI-99, SECR or SECR without frame mass

A simple EI-99 model captures major impacts caused by material production, use and disposal in Case A (Baayen 2000). This work compares two different versions of SECR with EI-99. The first version of SECR (Case B) considers the entire mass of the log splitter while the second (Case C) accounts for the mass of only the active (“living”) parts of the design. Active parts are defined as the engine, pump, hydraulic cylinder and control valve.

A hydraulic log-splitter model originally developed by Malak relates the design variables to the mathematical representations of the stated goals (Malak 2008). Each design variable is a key characteristic of one of four components: engine, pump, hydraulic cylinder and control valve. Specifications for the four modeled components dictate the allowable values for design variables and associated parameters. Notable modifications to Malak’s model include the addition of an environmental impact model and presentation of the design problem in the form of a Compromise Decision Support Problem (cDSP) (Mistree, et al. 1993, Mistree, et al. 1994). Presentation of the model in cDSP format follows.

Given:

Relevant Information for Log-Splitter Design

System Parameters

$\tau \equiv (\text{var}\,ies)$	max. engine torque	[ft-lbf]
$s_{mpeng} \equiv (\text{var}\,ies)$	engine speed at max. power	[rev/min]
$s_{mteng} \equiv (\text{var}\,ies)$	engine speed at max. torque	[rev/min]
$m_{eng} \equiv (\text{var}\,ies)$	engine weight	[lbf]
$c_{eng} \equiv (\text{var}\,ies)$	engine cost	[$]
$s_{\max pump} \equiv (\text{var}\,ies)$	max. pump speed	[rpm]
$\varepsilon_{pump} \equiv (\text{var}\,ies)$	mechanical efficiency of the pump	
$m_{pump} \equiv (\text{var}\,ies)$	pump weight	[lbf]
$c_{pump} \equiv (\text{var}\,ies)$	pump cost	[$]
$d_{cyl} \equiv (\text{var}\,ies)$	bore diameter of hydraulic cylinder	[in]
$m_{cyl} \equiv (\text{var}\,ies)$	cylinder weight	[lbf]
$c_{cyl} \equiv (\text{var}\,ies)$	cylinder cost	[$]
$m_v \equiv (\text{var}\,ies)$	control valve weight	[lbf]
$c_v \equiv (\text{var}\,ies)$	control valve cost	[$]
$t \equiv 2$	operating life of a log-splitter	[yr]
$P_r \equiv 2500$	relief valve pressure	[psi]

System Constants

$\eta_{eng} \equiv .15$	First Law thermal efficiency of an engine	
$e_{st} \equiv 86$	Eco-Indicator 99 environmental impact for steel	[mPt/kg]
$e_{stlf} \equiv 1.4$	Eco-Indicator 99 environmental impact for steel placed in a landfill	[mPt/kg]
$e_{gas} \equiv 210$	Eco-Indicator 99 environmental impact for gasoline	[mPt/kg]
$h_{lhv} \equiv 42.5$	Lower heating value of gasoline	[MJ/kg]

Relevant Equations

$A_{bore} = \dfrac{\pi d_{cyl}^2}{4}$	interior cross-sectional area (bore area) of hydraulic cylinder	[in^2]
$m_t = 56.52W - 137.41$	total mass of log-splitter based on regression of existing devices	[kg]
$m_{comp} = 0.4539(m_{eng} + m_{pump} + m_{cyl} + m_v)$	mass of components	[kg]
$c_{comp} = c_{eng} + c_{pump} + c_{cyl} + c_v$	cost of log-splitter's primary components	[$]
$P_a = \dfrac{75.39\tau\varepsilon_{pump}}{\Delta_{pump}}$	available pressure	[psi]
$P_{op} = \min(P_a, P_r)$	operating pressure	[psi]
$F_{ram} = A_{bore}P_{op}$	ram force	[lbf]

$s_{\max 1} = \min\left(s_{\max pump}, s_{mpeng}\right)$	max. operating speed at max. engine power	[rpm]
$V_{pump1} = 0.004329 s_{\max 1} \Delta_{pump}$	pump flow rate at max. engine power	[gal/min]
$V_{pumpA} = \dfrac{1714 \tau \varepsilon_{pump}}{P_r}$	alternate pump flow rate at max. engine power	[gal/min]
$V_{\max 1} = \min\left(V_{pump1}, V_{pumpA}, V_v\right)$	max. pump flow rate at max. engine power	[gal/min]
$t_{c1} = \dfrac{.26 A_{bore}(6)}{V_{\max 1}}$	6" cycle time at max. engine power	[s]
$s_{\max 2} = \min\left(s_{\max pump}, s_{mteng}\right)$	max. operating speed at max. engine torque	[rpm]
$V_{pump2} = 0.004329 s_{\max 2} \Delta_{pump}$	pump flow rate at max. engine torque	[gal/min]
$V_{\max 2} = \min\left(V_{pump2}, V_v\right)$	pump flow rate at max. engine torque	[gal/min]
$t_{c2} = \dfrac{.26 A_{bore}(6)}{V_{\max 2}}$	6" cycle time at max. engine torque	[s]
$t_c = t_{c1} + t_{c2}$	total cycle time	[s]
$I_{mat} = 0.4539 e_{st}\left(m_{eng} + m_{pump} + m_{cyl} + m_v\right) + e_{st}\left(m_t - m_{comp}\right)$	environmental impact of material production	[mPt]
$I_{use} = \dfrac{23512 W e_{gas} t}{\eta_{eng} h_{lhv}}$	enviro. impact of log-splitter use phase	[mPt]
$I_{disp} = 0.4539 e_{stlf}\left(m_{eng} + m_{pump} + m_{cyl} + m_v\right) + e_{stlf}\left(m_t - m_{comp}\right)$	environmental impact of disposal	[mPt]
$I = I_{mat} + I_{use} + I_{disp}$	total environmental impact	[mPt]
$\Omega_B = \dfrac{745.7W}{m_t}$	mass specific energy consumption rate using total log-splitter mass	[W/kg]
$\Omega_C = \dfrac{745.7W}{m_{comp}}$	mass specific energy consumption rate using only component mass	[W/kg]

Find:

System Variables

$W \equiv$	engine power	[hp]
$\Delta_{pump} \equiv$	pump displacement	[in^3/rev]
$l_{cyl} \equiv$	cylinder stroke length	[in]
$V_v \equiv$	maximum control valve flow rate	[gal/min]

Deviation Variables

$d_1^+ \equiv$ represents overachievement of ram force

$d_1^- \equiv$ represents underachievement of ram force

$d_2^+ \equiv$ represents overachievement of stroke length

$d_2^- \equiv$ represents underachievement of stroke length

$d_3^+ \equiv$ represents overachievement of cost

$d_3^- \equiv$ represents underachievement of cost

$d_4^+ \equiv$ represents overachievement of mass

$d_4^- \equiv$ represents underachievement of mass

$d_5^+ \equiv$ represents overachievement of cycle time

$d_5^- \equiv$ represents underachievement of cycle time

$d_6^+ \equiv$ represents overachievement of environmental impact (either EI-99 or SECR)

$d_6^- \equiv$ represents underachievement of environmental impact (either EI-99 or SECR)

Satisfy:

System Constraints

Pressure Constraint

$$P_r - P_{op} \geq 0 \qquad \text{[psi]}$$

Speed Constraints

$$4000 - s_{\max pump} \geq 0 \qquad \text{[rpm]}$$

$$4000 - s_{mpeng} \geq 0 \qquad \text{[rpm]}$$

$$2900 - s_{mteng} \geq 0 \qquad \text{[rpm]}$$

Flow Rate Constraints

$$V_v - V_{\max 1} \geq 0 \qquad \text{[rpm]}$$

$$V_v - V_{\max 2} \geq 0 \qquad \text{[rpm]}$$

System Goals

Meet high target for ram force

$$\left(\frac{F_{ram}}{F_{goal}}\right) + d_1^- - d_1^+ = 1 \qquad F_{goal} = 49088 \qquad \text{[lbf]}$$

Meet high target value stroke length

$$\left(\frac{l_{cyl}}{L_{goal}}\right) + d_2^- - d_2^+ = 1 \qquad L_{goal} = 60 \qquad \text{[in]}$$

Meet low target value for cost

$$\left(\frac{c_{goal}}{c_{comp}}\right) + d_3^- - d_3^+ = 1 \qquad c_{goal} = 545 \qquad \text{[\$]}$$

Meet low target value for mass

$$\left(\frac{m_{goal}}{m_t}\right) + d_4^- - d_4^+ = 1 \qquad m_{goal} = 60 \qquad \text{[kg]}$$

Meet low target value for cycle time

$$\left(\frac{t_{goal}}{t_c}\right) + d_5^- - d_5^+ = 1 \qquad t_{goal} = 0.37 \qquad \text{[s]}$$

Meet low target value for enviro. impact as EI-99 OR

$$\left(\frac{I_{goal}}{I}\right) + d_6^- - d_6^+ = 1 \qquad I_{goal} = \left(2.71x10^6\right)t \qquad \text{[mPt]}$$

Specific energy consumption rate

$$\left(\frac{\Omega_{goal}}{\Omega}\right) + d_6^- - d_6^+ = 1 \qquad \Omega_{goal} = 10 \qquad \text{[W/kg]}$$

System Bounds

$3.5 \le W \le 16$ [hp]

$0.072 \le \Delta_{pump} \le 2.93$ [in^3/rev]

$8 \le l_{cyl} \le 60$ [in]

$16 \le V_v \le 30$ [gpm]

$d_1^- \bullet d_1^+ = 0$

$d_1^-, d_1^+ \ge 0$

$d_2^- \bullet d_2^+ = 0$

$d_2^-, d_2^+ \ge 0$

$d_3^- \bullet d_3^+ = 0$

$d_3^-, d_3^+ \ge 0$

$d_4^- \bullet d_4^+ = 0$

$d_4^-, d_4^+ \ge 0$

$d_5^- \bullet d_5^+ = 0$

$d_5^-, d_5^+ \ge 0$

$d_6^- \bullet d_6^+ = 0$

$d_6^-, d_6^+ \ge 0$

Minimize:

Deviation Functions

Case A: EI-99

$$Z_A = w_1 d_1^- + w_2 d_2^- + w_3 d_3^- + w_4 d_4^- + w_5 d_5^- + w_6 d_6^- \qquad \text{Such that } \sum_{i=1}^{6} w_i = 1$$

Case B: Specific energy consumption rate using total mass

$$Z_B = w_1 d_1^- + w_2 d_2^- + w_3 d_3^- + w_4 d_4^- + w_5 d_5^- + w_6 d_6^- \qquad \text{Such that } \sum_{i=1}^{6} w_i = 1$$

Case C: Specific energy consumption rate using only active component mass

$$Z_C = w_1 d_1^- + w_2 d_2^- + w_3 d_3^- + w_4 d_4^- + w_5 d_5^- + w_6 d_6^- \qquad \text{Such that } \sum_{i=1}^{6} w_i = 1$$

5.2.2 Resultant Log-Splitter Designs Using Eco-Indicator 99 and SECR

In this section, three design scenarios illuminate the log-splitter design space and provide insight into SECR's predictive capacity. The first scenario weights all goals evenly while the second ignores the environmental performance goal. The final scenario examines differences between the environmental metrics by placing total emphasis upon environmental performance.

Table 39: Design variable values for each environmental model case when all goals are equally weighted

Design Variables	Case A	Case B	Case C
Engine Power (hp)	3.5	3.5	3.5
Pump Displacement (in^3/rev)	0.072	0.072	0.072
Cylinder Stroke Length (in)	48	48	60
Maximum control valve flow rate (gal/min)	20	20	20

Table 39 and Table 40 respectively contain three log-splitter designs and sets of deviation variables for each design. Cases A-C refer to the three different environmental metrics used in deviation functions Z_A-Z_C. As Table 39 shows, equally weighted goals drive the design to almost the same configuration regardless of the environmental metric used. Only Case C results in a different design, but even there, only the cylinder is different. This outcome supports the chapter's hypothesis that SECR is predictive of environmental impact. However, one should note that this configuration delivers low to middling deviation variable values for four of the five technical goals. It is conceivable that this solution is selected as much for its technical soundness as its environmental performance.

Table 40: Deviation function and variable values for Cases A (EI-99), B (total mass SECR) and C (component mass SECR) at the given deviation variable weights

Case	Z	d_1^-	d_2^-	d_3^-	d_4^-	d_5^-	d_6^-
Weights	NA	1/6	1/6	1/6	1/6	1/6	1/6
A	0.278917	1.25E-05	0.2	0.465146	0.012508	0.994563	0.001272
B	0.406571	1.25E-05	0.2	0.465146	0.012508	0.994563	0.767199
C	0.381693	0.19001	0	0.476887	0.012508	0.993288	0.617465

To explore the potential dominance of technical performance criteria, one solves the problem subject to a weighting scenario that ignores environmental impact (w_6=0). Each case in Table 41 produces the same design because this scenario ignores the environmental metrics that differentiate them. The selected design is the same as that chosen in the previous scenario. This result shows the technical superiority of the selected design and indicates that the designs in Table 39 and Table 40 are more the product of technical advantage than environmental performance.

Table 41: Design variable values for each environmental model case when technical goals are equally weighted and environmental performance is ignored (w_1…w_5=0.2, w_6=0)

Design Variables	Case A	Case B	Case C
Engine Power (hp)	3.5	3.5	3.5
Pump Displacement (in^3/rev)	0.072	0.072	0.072
Cylinder Stroke Length (in)	48	48	48
Maximum control valve flow rate (gal/min)	20	20	20

Table 42: Deviation function and variable values for Cases A-C at the given deviation variable weights

Case	Z	d_1^-	d_2^-	d_3^-	d_4^-	d_5^-	d_6^-
Weights	NA	0.2	0.2	0.2	0.2	0.2	0
A	0.334446	1.25E-05	0.2	0.465146	0.012508	0.994563	0.001272
B	0.334446	1.25E-05	0.2	0.465146	0.012508	0.994563	0.767199
C	0.334446	1.25E-05	0.2	0.465146	0.012508	0.994563	0.650334

Placing the entire design emphasis on environmental performance (w_6 = 1) allows one to safely test for differences in guidance offered by the three metrics. Free from the need to satisfy any technical objectives, important differences emerge (See Table 43). Cases A and C lead to the selection of the smallest engine (3.5 hp) in the available set while Case B guides the design toward the largest one (16 hp). Case A and C differ in that Case C's SECR metric drives the design toward the largest pump, cylinder and control valve in the parts lists.

Table 43: Design variable values for each environmental model case when environmental performance is the only consideration (w_6=1)

Design Variables	Case A	Case B	Case C
Engine Power (hp)	3.5	16	3.5
Pump Displacement (in^3/rev)	0.072	0.072	2.92
Cylinder Stroke Length (in)	8	8	60
Maximum control valve flow rate (gal/min)	16	16	25

Engine choice differences represent especially radical differences in design. As modeled, use phase impacts dominate the EI-99 environmental impact estimate, and energy consumption in the form of gasoline dominates the use phase. Selecting a large engine produces decisively high EI-99 environmental impacts. The SECR metric in Case B took the design to a radically different part of the design space than the EI-99 metric in Case A. One can understand the reason for this difference by considering the formula for SECR in Case B and by examining the deviation variable values in Table 44.

Table 44: Deviation function and variable values for Cases A-C at the given deviation variable weights

Case	Z	d_1^-	d_2^-	d_3^-	d_4^-	d_5^-	d_6^-
Weights	0	0	0	0	0	0	1
A	0.001272	0.19001	0.866667	0.363258	0.012508	0.993288	0.001272
B	0.355882	0.19001	0.866667	0.458207	0.921927	0.993142	0.355882
C	0.578787	0.973411	0	0.681436	0.012508	0.980062	0.578787

Case B SECR (Ω_B) is a ratio of engine power to total log-splitter mass. Total log-splitter mass is an empirically derived function of engine power. Increased engine power also meant increased system mass. Note that the high value for the mass deviation variable ($d_4 = 0.9219$) in Table 44 indicates poor achievement of the minimization of mass goal. Though not obvious from its functional form, Ω_B declines with increasing power as a result of the relationship between engine size and system mass. Therefore, the maximization of engine power leads paradoxically to the minimization of specific energy consumption rate in Case B via the maximization of system mass.

The differences between Case A and C are more easily explained. Both metrics pushed the solution toward the smallest engine. As previously explained, Case A favored low power engines to avoid high EI-99 use phase impacts. SECR in Case C (Ω_C) only considered active components; so, its denominator was modeled as the sum of the four selected components, not as a function of engine power. Consequently, increases in engine power did not lead to the same decline in Ω_C as observed for Ω_B. The solver minimized Ω_C by minimizing engine power. It also minimized Ω_C by maximizing the mass of the other three components, which explains selection of the heaviest pump, cylinder and valve.

5.2.3 Exploring the Full Solution Space

Exploration of the solution space yields further insight into the predictive capacity of the SECR metrics. In Figure 38, one sees two plots of EI-99 against SECR. Each plots the points generated by evaluating the EI-99 score and SECR value for more than 1.1 million log-splitter design variants. The two plots reveal two decidedly different relationships between EI-99 and the different SECR metrics. Overall, the plots reinforce observations made about the influence of the bio-inspired metrics in Section 5.2.2.

For Case B SECR, the plot shows an inverse correlation between environmental impact and SECR based on total system mass. It illustrates the divergence between log-splitters optimized for EI-99 and Case B SECR first observed in Table 43. As explained in Section 5.2.2, the divergence emerges as a consequence of the relationship between total log-splitter mass and engine mass.

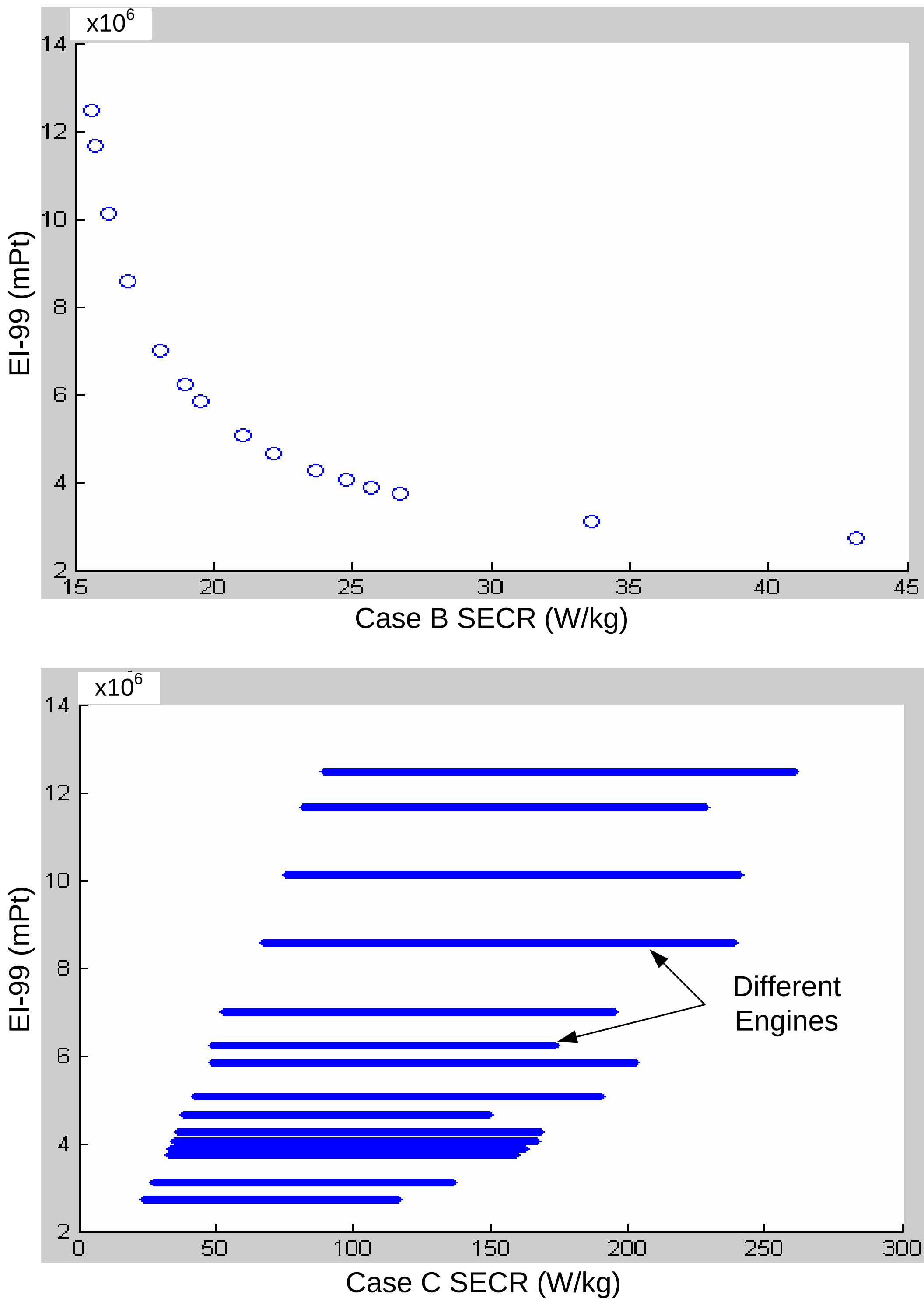


Figure 38: EI-99 vs. total mass SECR (Case B) and component mass SECR (Case C) for 1,137,600 log-splitter design variants

For Case C SECR, one notices three important features of the graph in Figure 38. First, one sees a positive correlation with EI-99, but one also observes proportionally large variations in SECR for comparatively narrow ranges of EI-99 values. Figure 39 helps explain this variation as well as the difference between the optimal Case A and C designs in Table 43.

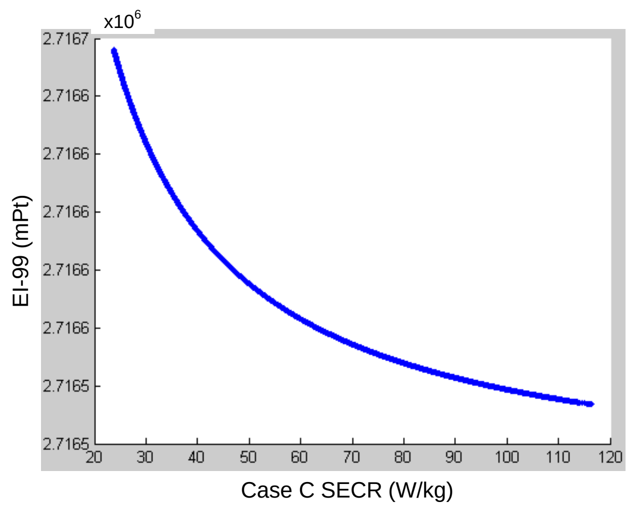


Figure 39: EI-99 vs. Case C SECR for log-splitter design variants using a 2.61 kW (3.5 hp) engine

Plotted for a single engine, Figure 39 illustrates that a roughly 200 mPt range in EI-99 is hidden by the larger scale in Figure 38. This range results from differences in component production and disposal impacts for different pump, cylinder and valve combinations. One may also notice that the lowest SECR value occurs at the highest EI-99 value. This fact explains the difference between the optimal designs for Cases A and C in Table 43. Finally, the curious stair-step stack of lines in Figure 38's Case C plot is the result of different engine power ratings for the different designs. Use phase energy consumption has the greatest impact on the log-splitter's EI-99 score; so, jumps from lower to higher power engines explain the gaps between the lines.

5.2.4 Learning from the Log-Splitter

At first blush, the log-splitter problem's solution appears to support the position that SECR can predict environmental impact. The equally weighted design scenarios in Table 39 generated approximately the same solutions. However, closer examination of design results shows that one form of SECR is inappropriate while the other displays less than desirable characteristics for a predictive environmental impact metric.

The total mass SECR metric used in Case B generates radically different designs than EI-99. The designs primarily differ in the selection of the most environmentally damaging component of the log-splitter – the engine. The Case B metric guides the design toward a large engine while EI-99 pushes it toward a small one. Furthermore, a solution space plot in Section 5.2.3 reveals an inverse correlation between EI-99 and total mass SECR. The total mass SECR metric used in Case B is clearly misleading in this design problem and may prove similarly troublesome in others. It lacks predictive capability.

The active mass SECR metric drove the log-splitter design into a region of the design space similar to EI-99, but it also lead to the selection of more massive components. Case C SECR also correlates with EI-99, as seen in Section 5.2.3. However, a proportionally large degree of variation exists in this correlation. It is predictive but not precise. Additionally, use of this metric in problems with environmental impacts driven by factors other than energy may lead to misleading recommendations.

The results of this case study lead to practical implications beyond those related to guideline evaluation. Had this section's use of bio-inspiration proved more successful, one would have been able to use product SECR in place of functional efficiency metrics such as volume of wood split per unit energy or passenger distance per unit energy. Functional efficiency metrics suffer from some of the same problems as functional unit definition in LCA (See Section 2.2.2.1). The variabilities and uncertainties encountered when evaluating product SECR make it less reliable than functional efficiency.

5.3 Comparing Existing Sustainability Metrics and SECR

To test the validity of the extended metabolism interpretation, one compares the specific energy consumption rates for societies with existing society level sustainability metrics. Validation hinges on a positive correlation between SECR and existing metrics and on correct identification of sustainable thresholds.

5.3.1 Sustainability Metrics for Societies

Before conducting the two part test to determine SECR's value as a society level sustainability metric, one must select appropriate sustainability metrics with which to compare it. To achieve a fair comparison, these existing metrics must attempt to capture the environmental (un)sustainability of a society. They must incorporate the sum of a society's activities, not simply part of its infrastructure. These metrics must also focus on the physical, biological and ecological components of sustainability, since the extended metabolism interpretation of this chapter's guideline is silent on economic and social matters.

Table 45: Existing sustainability metrics

#	Name	Description
1	Ecological Footprint (EF)	EF measures mankind's demand for resources and services in terms of land and land equivalents needed to deliver them (Wackernagel, et al. 1996). A second part of EF analysis estimates the amount of land available to provide these services. When calculated for all nations, one can estimate the ratio of needed to available land on Earth, providing an absolute threshold for environmental sustainability.
2	Environmental Sustainability Index (ESI)	The developers' method aggregates 76 variables into 21 indicators for 5 components that are equally weighted to produce the ESI (Esty, et al. 2005). The five components deal with the state of environmental systems, stresses on those systems, human vulnerability, institutional capacity and global stewardship.
3	Environmental Vulnerability Index (EVI)	Meant for use at the national scale, EVI aggregates 50 indicators dealing with the risk of environmental events (natural or anthropogenic), resistance to environmental events and past environmental damage (Kaly, et al. 2004). It combines weather, geology, geography, resource and population related metrics to gage hazards, resistance and past damage. The developers established sustainable thresholds for each indicator by analyzing observed values.

Table 45 lists and describes three noteworthy metrics for sustainability that one can apply at the national scale or greater. Each provides insight into relative or absolute sustainability. However, only EF analysis is appropriate for comparison with SECR. EF focuses on the physical, biological and ecological components of sustainability. It also uses Earth's available productive land as a threshold for environmental sustainability. In contrast, ESI and EVI are weighted indices that include social, economic and geographic factors. ESI is an entirely relative metric while EVI relies on analysis of observed values to set environmental sustainability thresholds for each indicator (Kaly, et al. 2004). As a practical note, a lack of times series ESI and EVI values limits one's ability to identify trends. Therefore, the following sections test the value of the extended metabolism interpretation by comparison with EF.

5.3.2 National and Global Correlations

Quantitative validation of the extended metabolism interpretation begins by testing the correlation between SECR and EF at the national level. The following graphs and tables contain the results of this test. They indicate that a correlation exists between and within nations.

Consider Figure 40. It graphs the per capita ecological footprint for selected nations against the SECR for each nation. While notable variation is present ($R^2 = 0.72$), the positive upward trend is clear. Increasing the rate of energy consumption per unit mass of a citizen correlates with increased ecological footprint per citizen in each country.

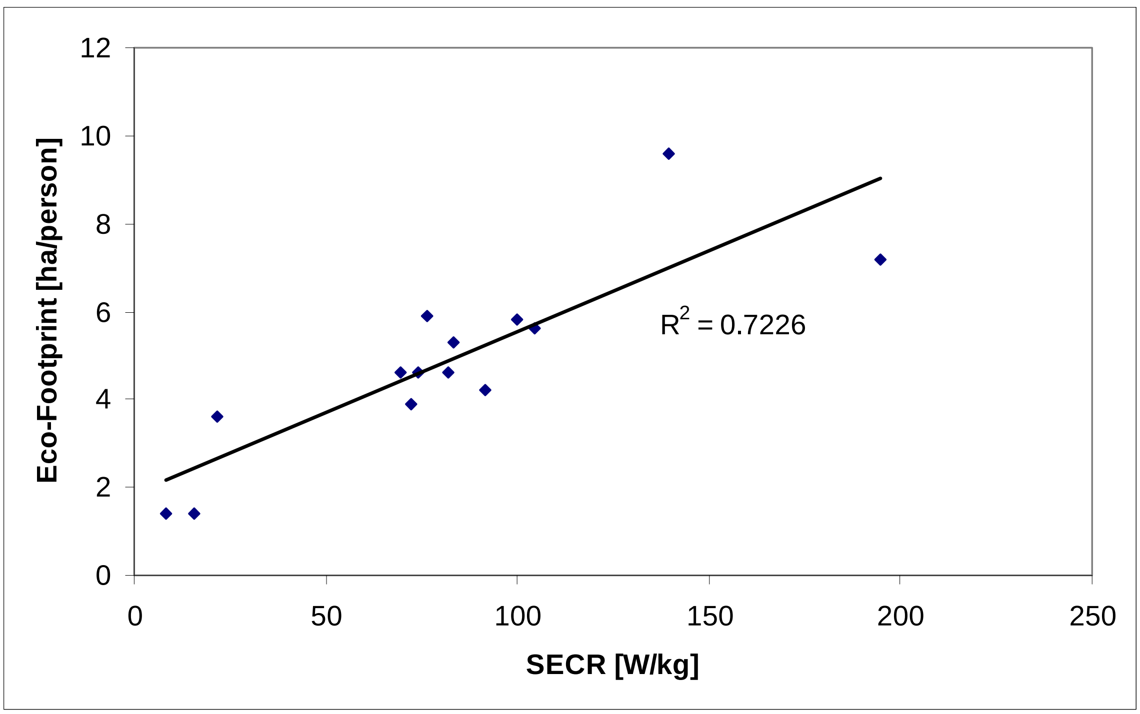


Figure 40: EF per person vs. SECR for selected countries in 1995

Table 46: 1995 SECR and per capita eco-footprint data for selected countries (EF data from (Chambers, et al. 2000); energy consumption from (EIA 2008); body mass data from (WHO , Grandjean 1988, Cavelaars, et al. 2000, Ogden, et al. 2004, 2005b, 2005c, Noguerol, et al. 2005, Pol 2006, Vignerova, et al. 2006))

Country	Estimated Body Mass (kg)	SECR (W/kg)	Eco-Footprint (ha/person)
Brazil	67	24	3.6
Canada	71	196	7.2
China	61	18	1.4
Czech Republic	78	71	3.9
Denmark	74	77	5.9
Finland	74	107	5.8
France	70	87	5.3
Germany	79	74	4.6
Japan	60	96	4.2
Netherlands	74	108	5.6
Philippines	54	9	1.4
Switzerland	70	83	4.6
United Kingdom	78	71	4.6
United States	82	140	9.6

Box: Method for Estimating Average Body Mass by Country

1. Average body mass index (BMI) was calculated as a weighted average of the fraction of each country's population falling into the four international BMI classifications: underweight, normal weight, overweight and obese. The fractions were obtained by querying the World Health Organization's global BMI database (WHO) only the most recent estimates were used.
2. Average heights for each country were obtained from a variety of sources (WHO , Grandjean 1988, Cavelaars, et al. 2000, Ogden, et al. 2004, 2005b, 2005c, Noguerol, et al. 2005, Pol 2006, Vignerova, et al. 2006).
3. Average BMI was multiplied by the square of average height to determine average body mass for each country.
4. In the cases of the U.S., U.K. and the Netherlands, measured body mass data was readily available. Body masses calculated following the previously described procedure were found to have < 2% error in these cases, lending confidence to the accuracy of body masses for other nations.

Examining the EF-SECR relationship within countries over time reveals similar correlations. With a coefficient of determination approaching 0.95, China's total footprint grows in lockstep with its SECR (See Figure 41). A rise in SECR explains 86% of the variation in footprint seen in Portugal and a majority of the variation seen in the United States (See Figure 42 and Figure 43). A number of other developing and developed nations display similar positive correlations between EF and SECR (See Table 48).

Table 47: SECR and EF data for China, Portugal and the United States

Year	*China*		*Portugal*		*United States*	
	SECR (W/kg)	**EF (ha)**	**SECR (W/kg)**	**EF (ha)**	**SECR (W/kg)**	**EF (ha)**
1961	NA	NA	NA	NA	101.5	9.64E+08
1965	NA	NA	NA	NA	113.3	1.34E+09
1969	NA	NA	NA	NA	131.9	1.49E+09
1973	NA	NA	NA	NA	145.6	1.83E+09
1977	NA	NA	NA	NA	144.3	1.95E+09
1981	9.5	1.16E+09	18.0	2.77E+07	135.2	1.93E+09
1985	11.4	1.32E+09	27.0	2.47E+07	131.0	2.06E+09
1989	13.1	1.56E+09	33.9	3.28E+07	140.2	2.13E+09
1993	14.4	1.61E+09	37.0	3.99E+07	138.5	2.11E+09
1997	16.6	2.01E+09	43.2	4.32E+07	144.2	2.36E+09
2001	17.5	2.12E+09	50.2	5.19E+07	137.7	2.53E+09
2005	28.1	2.73E+09	50.2	4.82E+07	138.5	2.59E+09

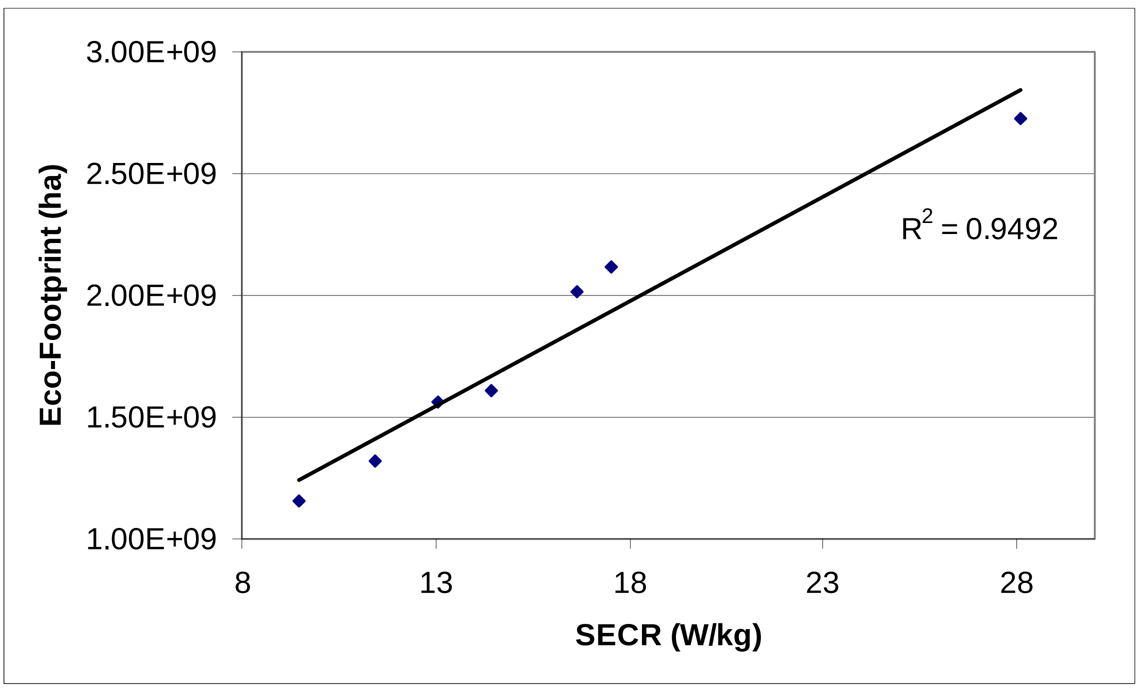


Figure 41: EF vs. SECR for China from 1981-2005

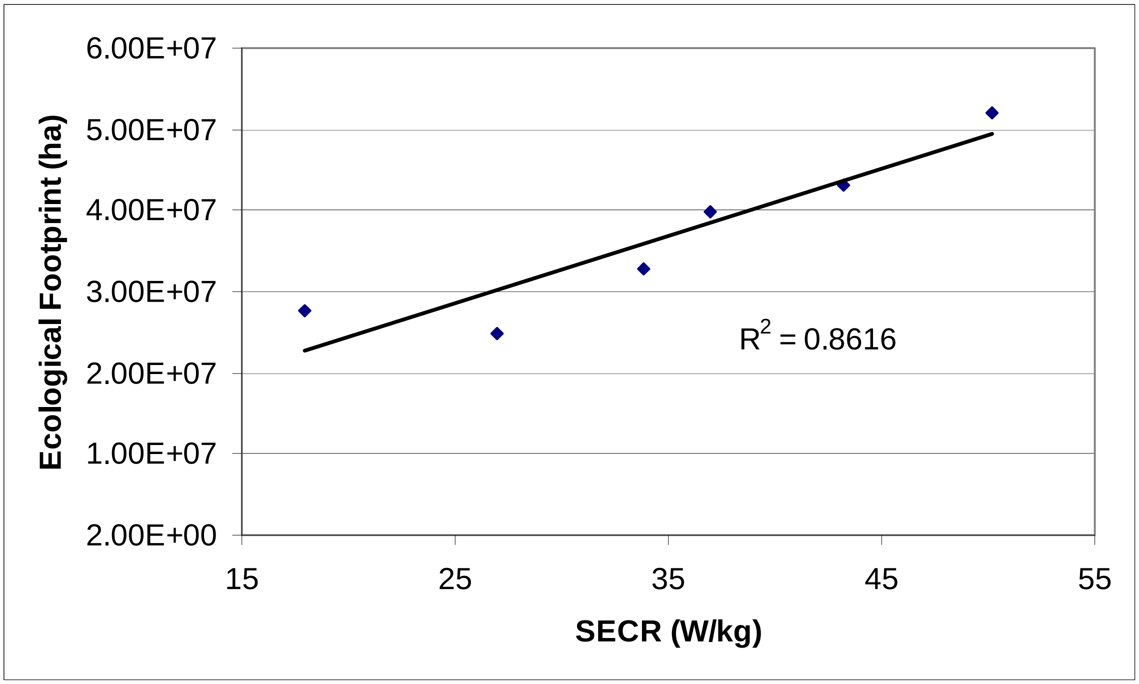


Figure 42: EF vs. SECR for Portugal from 1981-2005

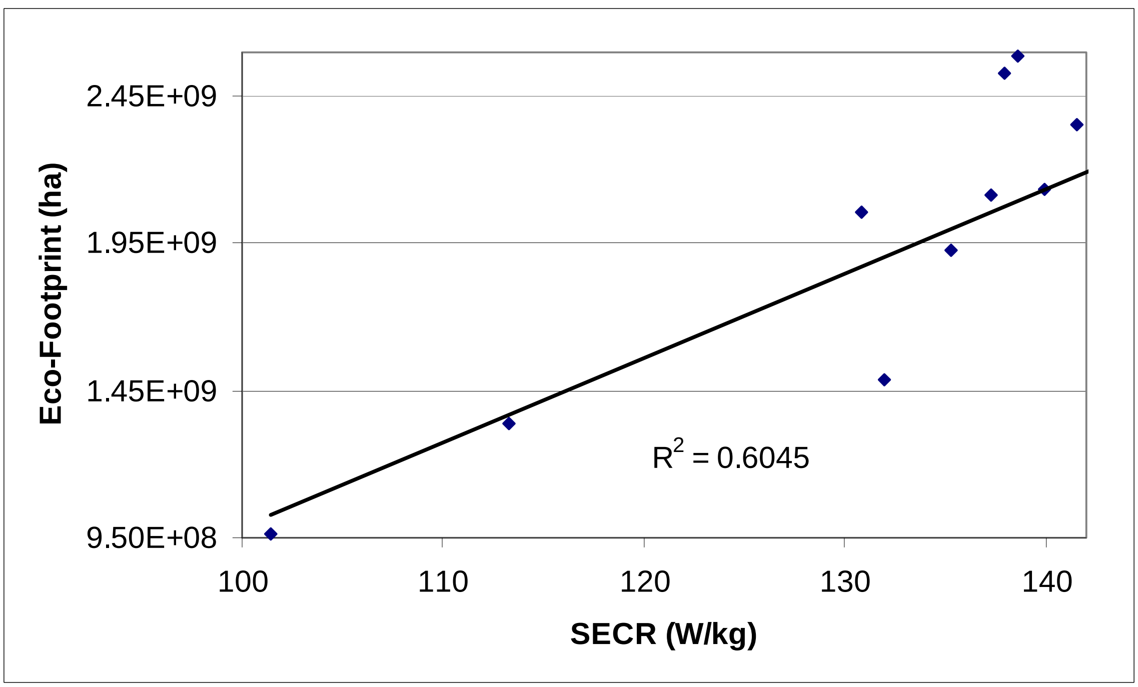


Figure 43: EF vs. SECR for the U.S. from 1961-2005

Interestingly, higher variability appears to characterize the correlations for developed countries (See Table 48). The differences between R^2 values for countries such as the U.S. and China clearly illustrate this fact. Differences in population growth, per capita energy growth and agricultural efficiency help explain these differences. Developing countries exhibit higher population growth rates, and despite using less energy per kilogram of citizen, they often display higher growth rates in SECR. The United States managed to increase its SECR by roughly 50% in the same period (1981-2005) that China tripled its value. Climbing population and energy consumption both drive EF higher. Additionally, during the plotted period, developed countries tended to benefit from agricultural efficiency improvements that reduced the amount of land area needed for cultivation. Despite increasing SECR, these crop yield increases helped flatten and even decrease footprints in some developed countries, introducing variability into the fits.

Table 48: Coefficients of determination for the EF vs. SECR relationship in selected countries for data spanning the years 1981-2005

Country	Coefficient of Determination (R^2)
Brazil	0.89
China	0.95
Egypt	0.90
Philippines	0.95
Portugal	0.86
France	0.61
Japan	0.82
United Kingdom	0.64
United States	0.60

One can also find a rough correlation between EF and SECR at the global scale. Plotting global demand for ecologically productive land against mass specific energy consumption rate shows that both tended to rise between 1981 and 2005 (See Figure 44). Taken with the national results, the presence of these correlations supports the extended metabolism interpretation of the limits to power guideline. The particular values taken by global SECR during this time period are also of interest and will be discussed in the following section.

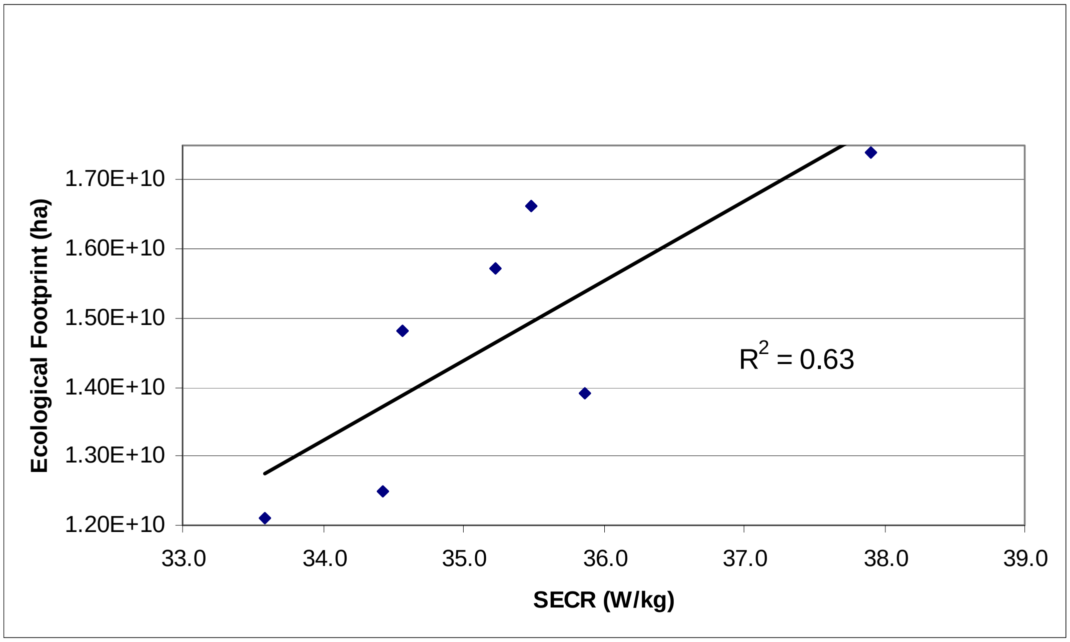


Figure 44: EF vs. SECR for the World from 1981-2005

5.3.3 Global and National Thresholds

Figure 44 in Section 5.3.2 shows the correlation between EF and SECR, but the x-axis of the graph tells an equally important story. Humanity approached the 40 W/kg threshold for metabolic activity. During the same period, footprint analysis reveals that humanity's demand for ecologically productive land surpassed the amount of ecologically productive land available (GFN 2008). Ratio values in Table 49 indicate the fraction of available land demanded; values >1 (one Earth) represent a level of demand exceeding that which Earth can provide on a sustainable basis.

Table 49: EF Ratio and SECR values for the years 1980-2005

Year	Footprint to Biocapacity Ratio	SECR (W/kg)
1980	0.949	33.7
1985	0.980	34.3
1990	1.09	35.0
1995	1.11	35.6
2000	1.19	36.3
2005	1.31	36.9

Interpolating the data in Table 49 reveals that humanity consumed all of Earth's available land starting in 1986. The 1986 SECR value of 34.4 W/kg comes remarkably close to the 40 W/kg threshold drawn from biology literature. Only a 16% error separates the biologically derived upper limit for society's safe metabolism from that determined using EF analysis.

National carbon sequestration rates represent a simpler, less assumption laden form of sustainability metric. Arguably, a nation must not emit more CO_2 than its lands can sequester in order to achieve sustainability. The U.S. sequestered 780.1 Gkg CO_2 equivalents in 2004 (EPA 2006). One can convert this sequestration figure into a specific energy consumption rate figure with estimates of national carbon intensity and average citizen body mass. Estimating America's 2004 carbon intensity using primary energy consumption data ($1.87\text{x}10^7$ J/kgCO_2) (EIA 2008) and CO_2 equivalent emissions ($780\text{x}10^9$ kgCO_2/yr) (EPA 2006), one calculates the mass specific consumption figure in Equation (13).

$$780.1x10^9\,\frac{kgCO_2}{yr}\,x\,\frac{1.87x10^7\,J}{kgCO_2}\,x\,\frac{1yr}{3.1536x10^6\,s}\,x\,\frac{1}{293x10^6\,people}\,x\,\frac{1person}{82kg}=19.3\frac{W}{kg} \qquad (13)$$

The 40 W/kg metabolism value is a rough field estimate; so, given its coarseness, the 19.3 W/kg figure falls reasonably near this biologically derived upper bound. Therefore, the limit on national sequestration also lends support to the extended metabolism interpretation of this chapter's guideline.

5.4 On the Question of Sustainable Energy Consumption Limits

Chapter 5 begins with an outline of a plan to test the validity of a biologically inspired engineering guideline.

Limit the rate of energy consumption per unit mass.

The opening paragraphs propose two types of tests. In the first, one looks for a correspondence in trends between established environmental metrics and mass specific energy consumption rate (SECR). In the second, one attempts to discern whether this metric's absolute metabolic boundary has analogs in traditional metrics. Both tests apply to the product and extended metabolism interpretations of the guideline. The results of these tests present a mixed picture.

One learns in Section 5.1 that commonly used products possess SECR values that straddle the biologically derived 40 W/kg boundary, hinting at the potential significance of this type of simple analysis. Section 5.2's in-depth application of this guideline in the form of a case study generates a far from clear picture about its significance at the product scale. Negative and positive correlations between SECR and a more traditional environmental impact metric appear. Where positive correlations appear, variation clouds the picture. Worse yet, nothing of particular interest (discontinuities, acceleration of impacts, etc.) occurs when design variants cross the 40 W/kg threshold. However, one must bear in mind that the traditional metric to which one compares SECR lacks an absolute reference point for sustainability. Indeed! Such a thing is undefined in EBDM.

A quantifiable definition exists at larger scales, scales relevant to the extended metabolism interpretation. Here, SECR gains purchase. One sees correlations with Ecological Footprint (EF). EF rises for individuals, countries and the globe as SECR rises. Most interestingly, SECR identifies the same threshold found using EF and CO_2 sequestration data. An argument grown from the roots of biology meets the canopy down approach responsible for EF and CO_2 limits based on sequestration.

However, one must take care not to assume that adherence to the dictates of the SECR guideline guarantee environmental sustainability. Other limits and principles bound and guide the lives of organisms and populations of organisms. One must expect that the same holds for society. While the SECR based guideline appears important, it likely is but one of a number of biologically rooted guidelines to which humanity should adhere. Indeed! The fullness of time and knowledge may reveal that moving humanity's energy systems away from the oxidation of carbon, a fundamental reaction in metabolism, frees society from this limit.

What, then, can one conclude about the limit on energy consumption per unit mass? Product SECR is potentially misleading and, even when helpful, may require identification of the active components of a design. SECR as a policy level metric holds more promise. One cannot lightly cast aside the ability to rapidly arrive at the same policy conclusion as methods founded on sustainable land use and sequestration levels. Clearly, some interpretations lack validity; yet, other interpretations emerge from Chapter

5 strengthened. The previous paragraphs wedged open something new in EBDM. Peering through the crack in opportunity's door one sees the first solid outlines of a foundation for sustainable engineering.

CHAPTER 6: EVALUATING THE ENVIRONMENTAL EFFICACY OF ECOLOGICALLY INSPIRED INDUSTRIAL NETWORKS

Chapter 6 concludes the evaluation process for the biological principles extracted and translated in Chapter 3. This chapter examines the dissertation's overarching proposition at the systems level. Specifically, Chapter 6 investigates the environmental efficacy of the bio-inspired guideline for industrial material flow networks.

Imbue industrial resource distribution networks with common living network patterns.

Two parallel comparisons and a network design case study evaluate the guideline's environmental efficacy. The chapter compares a sample composed of past, present and proposed industrial symbioses (eco-industrial parks and integrated bio-systems) to standard industrial networks in terms of environmental burdens and to ecosystems using biologically rooted metrics. The first comparison determines the environmental superiority or inferiority of industrial networks possessing biological characteristics. The second comparison determines the extent to which existing bio-inspired networks possess structures and material low regimes corresponding to those found in ecosystems. Together, these comparisons partially test the hypothesis that more biological industrial networks generate fewer relative or absolute burdens.

A material flow network case study serves as a further test of this hypothesis. It uses structural and material flow regime goals obtained while conducting the second comparison as goals in the design of a carpet tile material flow network. Comparing the resultant bio-inspired network to one designed using traditional cost and emission goals allows one to evaluate the environmental efficacy of the bio-inspired network guideline.

Section 6.1 presents the selected eco-industrial parks (EIP) and integrated bio-systems (IBS) used in the comparisons. This section also establishes the environmental efficacy of industrial symbioses. Sections 6.2 compares symbiosis and ecosystem network structures. Section 6.3 compares ecosystem material flow regimes with a well documented industrial symbiosis. Section 6.4 uses information gleaned in Sections 6.1-6.3 to guide the design of an industrial material flow network. In Section 6.5, one finds a reflection upon the outcomes in light of the dissertation's overarching proposition.

6.1 Defining and Motivating the Industrial Symbiosis – Ecosystem Comparison

Before conducting a meaningful comparison, one must know what is being compared, have something to compare and understand the significance of the comparison. This section accomplishes each of these tasks. It first defines industrial symbiosis and connects symbiosis with its biological roots. Then, the section lists EIP and IBS examples compared with ecosystems in later sections. Finally, the section describes the environmental significance of industrial symbiosis.

6.1.1 Industrial Symbiosis

Industrial symbiosis occurs when multiple firms or facilities achieve higher system efficiency through the exchange of "waste" energy and materials. An EIP is a type of industrial symbiosis that occurs among firms collocated in a bounded geographic area, typically an industrial park. An IBS is a type of symbiosis primarily built using collocated agrarian activities such as farming, animal husbandry and composting. Chertow views industrial symbiosis as, "…a collective approach to competitive advantage…" (Chertow 2000). As firms agree and learn to use wastes and by-products as process inputs, emissions and demands for virgin inputs fall, which reduces pollution control and resource costs. These cost reductions theoretically improve cooperating firms' competitive positions while decreasing environmental burdens.

Industrial ecologists trace the inspiration for this type of inter-firm cooperation to the biological ideas of mutualism and food web exchanges (Chertow 2000, Hardy, et al. 2002). The observed similarity between ecological networks (mutualist networks, food webs, etc.) and industrial symbioses makes each EIP a natural experiment in the application of system level bio-inspired guidance. It is for this reason that this chapter reviews the historical environmental impact of EIPs and investigates the extent of the similarity between symbioses and ecosystems.

6.1.2 Sample of Industrial Symbioses

The following tables list examined industrial symbioses and data sources available for each. The data cover EIPs and some IBSs. Approximately two thirds of the examined symbiosis were originally compiled and investigated by Hardy (Hardy 2001, Hardy, et al. 2002). Table 50 contains information about symbioses that exist or previously existed, while Table 51 lists proposed or planned symbioses. APPENDIX F holds the complete set of symbiosis data needed for the analyses conducted in Sections 6.1 to 6.3.

Table 50: Realized eco-industrial parks (EIPS) and integrated bio-systems (IBS)

#	Name	Description	Source
1	Gladstone (*EIP)*	Utilization of power production and mineral processing by-product and waste streams forms a resource cascade. The cascade connects sewage treatment, tire collection, solvent collection, power generation, cement production and two steps in aluminum production	(van Beers, et al. 2007)
2	Guayama (*EIP)*	A recently established resource cascade that links a waste water treatment plant to a petrochemical facility via a power plant	(Chertow, et al. 2005b)
3	Guitang Group (*EIP)*	Guitang's symbiosis centers on sugarcane farming and sugar production and also incorporates alcohol, cement, fertilizer, paper and power production. Its development spans four decades.	(Zhu, et al. 2004, Zhu, et al. 2007)
4	Kalundborg (*EIP)*	It is an oft cited and studied industrial symbiosis built around a power plant and a few other key industrial players that include an oil refinery, pharmaceutical plant and a wallboard manufacturer. It developed over the course of 25 years.	(Jacobsen 2006)
5	Kwinana (*EIP)*	A large and complex industrial symbiosis in Western Australia dominated by heavy industries that exchange waste water, energy and inorganic materials	(van Beers, et al. 2007)
6	Landskrona Industrial Symbiosis Programme *(EIP)*	This industrial symbiosis consists of existing and planned resource links built around a current district heating system and a waste management facility.	(Mirata, et al. 2005)
7	Monfort Boys Town IBS	A system meant to use brewery wastes to support multiple agricultural activities and biogas production	(Chertow 2000); http://www.zeri.org/ case_studies_pigs.htm
8	Nanning Sugar (*EIP)*	A sugarcane dependent symbiosis that integrates sugar, alcohol, pulp, paper and fertilizer production	(Yang, et al. 2008)
9	Red Hills EcoPlex (*EIP)*	A developing EIP built around a coal-fired power plant that could potentially integrate lumber, paper and concrete producers	(Hardy 2001)
10	Seshasayee Paper and Board Ltd.: Agro-industrial Eco-complex (*EIP)*	Originally established in order to guarantee a bagasse supply for a paper mill, this Indian EIP grew to incorporate sugar production, alcohol production and methane generation by linking waste and byproduct streams.	(Erkman, et al. 2000)
11	Tsumeb Brewery *(IBS)*	A development project that created an integrated bio-system by using waste grain and water flows to support biogas production and multiple agricultural activities	http://www.zeri.org/ case_studies_beer.htm

		Table 50 continued	
12	Uimaharju Forest Industry Park (*EIP)*	Uimaharju eco-industrial park began life as a sawmill in the 1950s. In time, other businesses moved into the region and began using the outputs, byproducts and wastes generated by established activities. In the final configuration, a sawmill, pulp mill and a combined heat and power plant form the core of an industrial cluster that also includes waste water treatment, gas recovery and ash treatment.	(Korhonen, et al. 2005)
13	Ulsan Industrial Park (*EIP)*	A set of water, energy and metal exchanges in an existing industrial park motivated by increasing environmental regulation and tougher competition	(Park, et al. 2008)

Table 51: Proposed eco-industrial parks (EIPS) and integrated bio-systems (IBS)

#	**Name**	**Description**	**Source**
1	AES Thames EIP	This proposed eco-park attempts to link material for soil, thermal energy, farm products and packaging materials by adding a brewery and a farm to an existing group of industries.	(Chertow 2002)
2	An Son Village *(IBS)*	A set of integrated village agricultural activities consisting of grain, animal and vegetable farming	(Hardy 2001)
3	Choctow EIP	A suggested redesign for an existing industrial complex that focuses on wastewater and used tire waste streams	(Carr 1998)
4	Clark Special Economic Zone	A proposed integration of solvent recovery, oil processing, tire processing, gray water treatment, composting and a power plant at a former American military base in the Philippines.	(Chertow 2002)
5	Connecticut Newsprint	An industrial symbiosis built around recycled newsprint	(Hardy 2001)
6	Devons EIP	This proposal seeks to establish and integrate activities meant to recycle and recover solvents, plastics, cardboard and biodegradable organic materials.	(Hardy 2001)
7	Fushan Farm *(IBS)*	A system that collects, converts, reuses and sells pig and chicken farm wastes with the aid of biogas producing waste digesters	http://www.fao.org/docrep/ T4470E/t4470e0q.htm
8	GERIPA *(IBS)*	A complex of industrial and agricultural activities centered around sugar and alcohol production	(Ometto, et al. 2007)
9	Hypothetical Landskrona Industrial Symbiosis Programme *(EIP)*	This proposed expansion of an existing EIP links water treatment, printing and glass products facilities to the existing network with utilizable waste and wastewater flows.	(Mirata, et al. 2005)

Table 51 continued			
10	Lower Mississippi Corridor	A proposed redesign of a petrochemical facility that adds multiple material cascades to the existing design	(Singh, et al. 2007)
11	Mongstad EIP	A proposed collocation of power production, aquaculture, gas capture and coal gasification with an existing oil refinery	(Zhang, et al. 2008)
12	PV Symbiosis Proposition	An eco-industrial park built around a multi-gigawatt photovoltaic (PV) module factory, this proposed eco-park is largely a resource cascade meant to support PV production.	(Pearce 2008)
13	Renova Resource Recovery Park	The proposed park's anchor tenant is a waste-to-energy facility intended to incinerate municipal waste and provide steam and electricity to many park tenants. The presence of fallow sugarcane fields near the park allows for the integration of agricultural components and agriculturally based activities	(Chertow 2002)
14	Stoneyfield Londonderry EIP	This proposed EIP is formed from an anchoring power plant and multiple agricultural activities (fruit processing, greenhouses, composting).	(Hardy 2001)
15	The Green Triangle	Proposed resource exchange between the Franklin Park Zoo, Arnold Arboretum and other nearby entities	(Hardy 2001)
16	Ulsan Industrial Park (*EIP)*	A proposed expansion of the existing Ulsan EIP that further utilizes waste water and incorporates wastewater sludge processing	(Park, et al. 2008)
17	Wallingford EIP	This composite of proposals aims at integrating collocated steel, concrete, plastic and power facilities. It emphasizes use of wastes such as water, scrap metal and ash.	(Chertow 2002)

6.1.3 Environmental Performance of Industrial Symbioses

One needs evidence that formation of symbioses results in environmental improvement to argue that biologically inspired guidance leads to system level betterment. To learn if such evidence is present, this section examines the literature on existing symbioses listed in Table 50. Data for selected symbiosis are examined with the intent of determining whether creation of these complexes reduces consumption and emissions on a relative or absolute basis.

Van Beers and coauthors documented the material and energy exchange networks in Australia's Kwinana Industrial Area and town of Gladstone (van Beers, et al. 2007). They reported the existence of multiple exchanges in Kiwana. In one set of exchanges, 10,000 metric tons of waste gypsum from a chemical plant and 1.1 GL of wastewater supply an alumina refinery, offsetting the need for virgin materials. In another, a cogeneration plant draws water and pressurized air from a pigment facility and returns electricity, superheated steam and wastewater. Around the town of Gladstone, they identified four major symbiotic links involving waste to energy, water reuse, conventional recycling and fly ash reuse. The water reuse project cut an alumina refinery's water usage by 6.5 ML/day and prevented the release of treated sewage effluent. The conventional recycling program eliminated waste sent to the landfill of the company that organized it.

A simple material and energy symbiosis among a wastewater treatment plant, coal-fired power plant and an oil refinery in Guayama, Puerto Rico generates multiple quantified environmental benefits (Chertow, et al. 2005a). By using treated effluent from a wastewater treatment plant as cooling water, the coal-fired station avoids the extraction of 15.1 ML of water per day. Purchasing process steam from the coal station allowed the oil refinery to eliminate process steam boilers, which cut total SO_2, NO_x and particulate emissions by 99.5%, 84.4% and 95.3%, respectively.

Two Chinese sugar based industrial complexes formed symbioses and reported relative environmental improvements. Nanning Sugar Co. Ltd. reorganized its operations to use waste materials from sugar production in alcohol, paper, cement and fertilizer production (Yang, et al. 2008). On a per monetary unit basis, Yang and Feng reported 62%, 59% and 35% decreases in chemical oxygen demand, SO_2 and water consumption, respectively. A similar integration of sugar, alcohol, paper, cement and fertilizer production by the Guitang Group reportedly lead to, "…increased efficiency and productivity per unit of input" (Zhu, et al. 2007).

Multiple researchers considered the environmental implications of Kalundborg, Denmark's famous industrial symbiosis (Ehrenfeld, et al. 1997, Chertow, et al. 2005a, Jacobsen 2006). Chertow and Lombardi noted that the symbiosis saves 3.3 Mm^3/yr. of ground and surface water as well as 20 ktons/yr. of oil and 200 ktons/yr. of natural gypsum (Chertow, et al. 2005a). A focused, though limited, analysis of liquid water and steam exchanges revealed avoided emissions totaling 154,788 metric tons of CO_2 and 389 metric tons of NO_x for the period between 1997 and 2002 (Jacobsen 2006). These and other data led Jacobsen to conclude that, "…significant and some smaller environmental savings are related to the individual IS exchanges based on water substitution and cascading…" (Jacobsen 2006).

Two integrated bio-systems meant to utilize the waste streams of breweries provide further evidence of the benefits of symbioses. The Monfort Boys Town system in Suva, Fiji uses spent grains that would otherwise damage a local coral reef ecosystem (Chertow 2000). A similar system in Tsumeb, Namibia reduces consumption of virgin food and energy resources by better utilizing spent grains (ZERI 2004).

A developing EIP in Ulsan, South Korea also displays evidence of the benefits of symbiosis. Exchange relationships between occupants provide recovered Cu, Zn and caustic material, averting the environmental burdens associated with conventional sourcing (Park, et al. 2008). The need for fossil energy consumption is reduced by using biogas produced by Ulsan City's landfill and wastewater treatment facility (Park, et al. 2008).

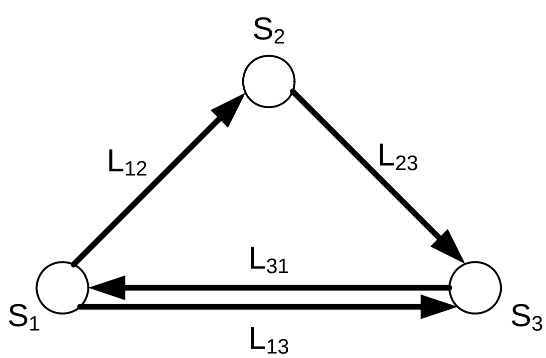
Multiple realized symbioses exhibit environmental benefits arising from there operations. Operation of these complexes reduces resource consumption, cuts emissions or both. The presented evidence indicates that these benefits can occur on an absolute basis as well as a relative basis (per unit of production). In the better documented cases, the literature quantifies these benefits. Therefore, one can argue that formation of these systems generally leads to environmental improvements. The way is now clear to explore the extent to which symbioses resemble ecosystems.

6.2 Structural Similarities in Living and Industrial Webs

To test the similarity between symbioses and ecosystems, this section presents data obtained by expanding upon a study originally conducted by Hardy and Graedel (Hardy 2001, Hardy, et al. 2002). Their study viewed EIPs through the lens of metrics traditionally used to quantify the structural characteristics of ecosystems. This study expands upon the original by increasing the data set from 19 to 29 parks and by adding an important structural metric, cyclicity. This work marks the first known application of cyclicity to the structural analysis of industrial symbioses. It compares EIP and biological structures to the characteristic linear material flow structure commonly found in current industry. It also notes the difference between proposed and realized symbioses.

6.2.1 Ecosystem Metrics for Industrial Symbioses

Table 52 contains structural metric values for symbioses listed in Table 50 and Table 51. Ecologists traditionally use these measures and metrics to quantify food web characteristics (Briand 1983, Briand, et al. 1987, Schoener 1989, Warren 1990).



$$\begin{array}{cc} & \text{Consumer} \\ \text{Resource} & \begin{bmatrix} L_{11} & L_{12} & L_{13} \\ L_{21} & L_{22} & L_{23} \\ L_{31} & L_{32} & L_{33} \end{bmatrix} = \begin{bmatrix} 0 & 1 & 1 \\ 0 & 0 & 1 \\ 1 & 0 & 0 \end{bmatrix} \end{array}$$

Figure 45: Example food web and community matrix representation

Formulas for these metrics appear in Figure 51, but the meaning and calculation of each is best understood within the context of a community matrix (See Figure 45). Each row in a community matrix captures the flow of resources from one species to all species in a web while each column captures the input of resources to a particular species from all species in the web. A value of 1 indicates the existence of a flow while a 0 indicates absence. Returning to Figure 45, a value of 1 for L_{13} indicates that species 1 (S_1)

contributes resources to (is eaten by) species 3 (S_3). Alternatively, one can interpret that element of the matrix to mean S_3 consumes S_1.

Number of species (S) – the number of species in a web; number of independent facilities in an industrial context

Number of links (L) – the number of links between species in a web; number of links between facilities in an industrial context

Links per species (L/S) – the ratio of links between species to number of species

Prey to predator ratio (Prey/Pred. ratio) – ratio of the number of species eaten by another species to the number of species that eat another species. This is the number of nonzero rows in a community matrix divided by the number of nonzero columns.

Specialized predator fraction – the number of predators eating only one species divided by the total number of predators in the web. This is the sum of the number of columns with only one nonzero element divided by the total number of columns with nonzero elements.

Generalization – average number of prey eaten per predator in a web. One generates this value by adding column sums in a community matrix and dividing this figure by the number of columns with nonzero elements.

Vulnerability – average number of predators per prey in a web. In a manner similar to generalization, one adds the row sums in a community matrix and divides by the total number of rows with nonzero elements to find vulnerability.

Connectance (L/S^2) – number of links in a web divided by topologically possible links in a web if one allows cannibalism; L/S(S-1) if one forbids cannibalism

<u>Cyclicity</u> – a measure of structural cycling obtained by finding the maximum eigenvalue of a web's structural adjacency matrix. It can be shown that the structural adjacency matrix is the transpose of the community matrix.

Table 52: Occupant (S), link (L) and assorted structural metrics for all eco-industrial parks and integrated bio-systems (realized EIPs and IBSs shaded)

EIP or IBS	S	L	L/S	Prey/Pred. ratio	Specialized Pred. frac.	Gen.	Vul.	C	Cyclicity
AES Montville	8	13	1.6	1.60	0.20	2.60	1.63	0.20	1.47
An Son	3	2	0.7	1.00	1.00	1.00	1.00	0.22	0.00
Clark	20	51	2.6	0.89	0.26	2.68	3.00	0.13	3.34
Conn Newsprint	6	5	0.8	0.40	1.00	1.00	2.50	0.14	0.00
Devons	21	30	1.4	1.21	0.57	2.14	1.76	0.07	1.73
Fushan Farms	7	9	1.3	0.71	0.71	1.29	1.80	0.18	1.27
GERIPA	8	15	1.9	0.75	0.25	1.88	2.50	0.23	1.93
Gladstone	8	7	0.9	2.00	0.33	2.33	1.17	0.11	0.00
Green triangle	8	25	3.1	0.88	0.25	3.13	3.57	0.39	3.87
Guayama	5	4	0.8	1.00	0.67	1.33	1.33	0.16	0.00
Guitang	7	12	1.7	0.86	0.43	1.71	2.00	0.24	1.62
Kalundborg	10	12	1.2	0.30	0.80	1.20	4.00	0.12	1.00
Kwinana	27	51	1.9	0.79	0.42	2.13	2.68	0.07	2.59
Landskrona	6	6	1.0	2.00	0.33	2.00	1.00	0.17	1.00
Landskrona prop	12	12	1.0	1.25	0.75	1.50	1.20	0.08	1.00
Lower Mississippi Corridor	23	40	1.7	0.78	0.44	2.22	2.86	0.08	1.00
Monfort	9	11	1.2	0.88	0.63	1.38	1.57	0.14	1.22
Mongstad	11	20	1.8	0.80	0.30	2.00	2.50	0.17	1.55
Nanning	8	12	1.5	0.75	0.50	1.50	2.00	0.19	1.40
PV	9	14	1.6	0.75	0.50	1.75	2.33	0.17	1.00
Red Hills	8	17	2.1	1.00	0.38	2.13	2.13	0.27	1.97
Renova	11	33	3.0	1.00	0.18	3.00	3.00	0.27	3.39
Sesha	7	12	1.7	0.86	0.43	1.71	2.00	0.24	1.62
Stoneyfield	13	28	2.2	0.83	0.50	2.33	2.80	0.17	1.00
Tsumeb	8	9	1.1	0.88	0.88	1.13	1.29	0.14	1.17
Ulsan	15	20	1.3	1.40	0.80	2.00	1.43	0.09	1.00
Ulsan prop	16	25	1.6	1.27	0.45	2.27	1.79	0.10	2.29
Wallingford	12	18	1.5	0.82	0.55	1.64	2.00	0.13	1.00
Uimaharju	6	10	1.7	0.83	0.67	1.67	2.00	0.28	2.00

Table 53 contains summary statistics for the metrics in Table 52, and Table 54 lists summary statistics for ecosystems (Briand 1983, Fath, et al. 2007). The average industrial and ecological web sizes differ. The ecological webs possess roughly twice the number of members and links. However, many of the other metrics take similar values for the two web types. With the exception of cyclicity, the metrics' percent differences range from a low of -4% for prey / predator ratio to a high of -37% for connectance. Average cyclicity for Fath's ecological webs far exceeds that observed in industrial webs, but it is important to interpret this result in light of Fath's observations about the cyclicity metric (Fath 2007, Fath, et al. 2007). He states that one may group cyclicity values into three categories with different meanings: 0 for no cycling, 1 for weak cycling and >1 for strong cycling (Fath, et al. 2007). Since both datasets possess average cycling values greater than unity, both fall into the strongly cyclic class of structures. It is important to note the minimums for this metric, though. All ecosystems exhibit strong cycling as indicated by a minimum cyclicity value of 1.62. In contrast, a minimum of 0 for cyclicity shows that some industrial webs lack a cyclic structure. A number of other industrial webs only achieve weak cycling by this measure.

Table 53: Summary statistics for all EIPs and IBSs in Table 52

	Mean	Stan. Dev.	Min.	Max.
S	10.8	5.7	3	27
L	18.0	12.9	2	51
L/S	1.6	0.6	0.7	3.1
Prey/Pred. ratio	0.98	0.38	0.30	2.00
Specialized Pred frac.	0.52	0.23	0.18	1.00
Gen	1.88	0.56	1.00	3.13
Vul	2.10	0.76	1.00	4.00
C	0.17	0.08	0.07	0.39
Cyclicity	1.46	0.97	0.00	3.87

Table 54: Summary Statistics for ecosystems based on data by Briand and Fath (Briand 1983, Fath, et al. 2007)

	Mean	Stan. Dev.	Min.	Max.
S	18.1	9.1	5	45
L	33.3	18.6	6	95
L/S	1.8	0.6	0.9	3.7
Prey/Pred. ratio	0.94	0.27	0.45	1.75
Specialized Pred frac.	0.403	0.205	0.000	0.875
Gen	2.32	0.68	1.29	4.33
Vul	2.64	1.03	0.86	6.79
C	0.12	0.06	0.02	0.27
Cyclicity	7.14	4.11	1.62	14.17

Taken together, these outcomes suggest some similarity between the structures of ecological and industrial webs. Expanding the industrial web dataset and adding an additional metric to the analysis has not altered Hardy and Graedel's conclusions about the similarity between the two types of webs (Hardy 2001, Hardy, et al. 2002). However, a larger eco-industrial park dataset allows a statistically more rigorous examination of these conclusions, the topic of the next section.

6.2.2 Plausibility of Structural Similarity

As mentioned, others gathered data and commented on the similarity in metric values for ecological and industrial symbiosis webs, but they did not formally propose or test any hypotheses about these webs. This section tests the hypothesis that it is plausible that ecological webs and industrial symbioses are manifestations of the same types of network structures.

It accomplishes this task by testing the following statistical hypothesis for each metric value. Using metric means for the ecological web dataset (μ_e) and the industrial symbiosis dataset (μ_s), one formulates null (H_0) and alternative (H_A) hypotheses.

$$H_0\text{: } \mu_e - \mu_s = 0 \text{ versus } H_A\text{: } \mu_e - \mu_s \neq 0$$

A 2-tail t-test result with p-values $\geq$ 0.05 would indicate that it is at least plausible that the metric means represent samples drawn from the same population. Multiple plausible readings for metric means would in turn show that it is plausible that the samples' structures come from the same population of structures. Table 55 contains the results for these statistical tests.

Table 55: Results of hypothesis tests for metric by metric comparison between all EIPs and ecosystem food webs

Metric	p-value (2-tail)
L/S	0.0843
Prey/Pred. ratio	0.6201
Specialized Pred frac.	0.0289
Gen	0.0051
Vul	0.0144
C	0.0102
Cyclicity	3.693E-07

As one readily sees, tests for most metrics generate p-values < 0.05. The link to species ratio falls in the gray area between rejection and acceptance of the null hypothesis, and only the prey to predator ratio with a p-value of 0.6201 indicates plausibility. This statistically significant comparison finds that it is not plausible that the two sets of structures hail from the same population of structures. This conclusion stands in contrast to those reached through qualitative analysis of structural metric values, and it is contrary to some of those drawn by Hardy and Graedel (Hardy 2001, Hardy, et al. 2002).

One must exercise caution in basing arguments about ecosystem similarity with industrial symbioses on only this test. Data quantity and comparison appropriateness both limit its persuasive power. When compared to the number and types of ecosystems found on Earth, the sample is vanishingly small, and one cannot be certain of its representativeness. Furthermore, the comparison may not prove the most fair or appropriate one. Designers, engineers and developers proposed and built the presented symbioses armed with only the vaguest notions of ecological networks. Ideas such as “waste equals food” and recycling served as their primary strategic guides. A more fair comparison might involve gauging the relative structural differences between ecosystems and symbioses on the one hand and ecosystems and traditional productions systems on the other.

6.2.3 Contrasting Linear Production, Symbioses and Ecosystems

Most production and consumption processes proceed in a linear fashion, leading to the “take, make, waste” society. Metrics previously applied to ecosystems and symbioses provide a quantitative understanding of the linear production system. Figure 46 graphs the values for a linear system of the same mean member size (11) as the investigated symbioses alongside the mean metric values for symbioses and ecosystems.

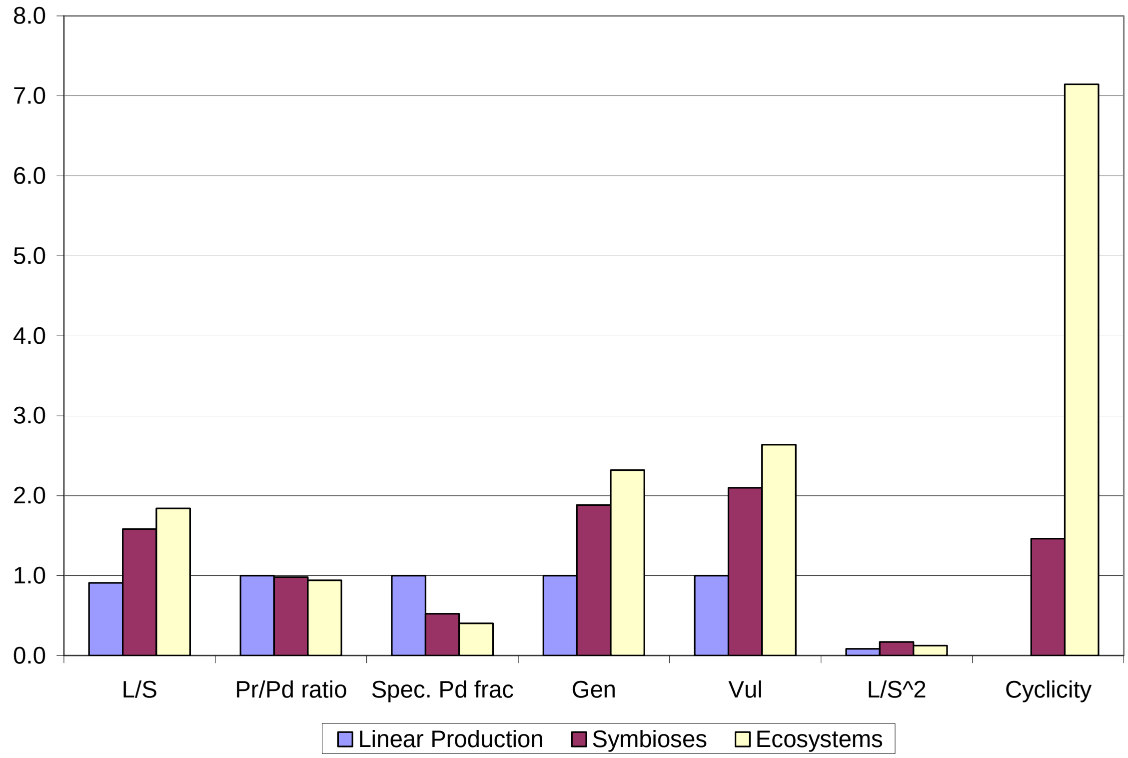


Figure 46: Structural metric comparison of a linear production chain, industrial symbioses and ecosystems

A trend of one kind or another appears for each metric value save connectance. In six of the seven cases, symbioses represent an intermediate structural form. They fail to reach metric values associated with ecosystems, but they prove closer to ecosystems than a linear system of production and consumption. This finding tends to support arguments that symbiosis creation tends to make production systems more ecological.

6.2.4 Proposed and Realized Symbioses

A comparison of the summary statistics for realized and proposed symbioses reveals a gap between ecological aspirations and implementation (See Table 56 and Table 57). In almost every structural category, proposed symbioses come closer to the ecological objective than realized ones. Mean link density is 1.8 for the ecosystem sample, 1.7 for proposed symbioses and 1.4 for realized ones. Ecological connectance is

0.12, proposed connectance is 0.17 and realized connectance is 0.18. Ignorance of ecological structures cannot explain the failure to reach the same values found in proposed industrial ecosystems. This suggests that factors other than design guidance may hinder creation of these networks.

However, splitting the 29 member EIP and IBS dataset into realized and proposed symbioses creates two smaller data sets with less statistical power. One should view any conclusions drawn from a comparison between the two as highly speculative.

Table 56: Summary statistics for realized EIPs and IBSs

	Mean	Stan. Dev.	Min.	Max.
S	9.7	6.0	5.0	27.0
L	14.7	12.2	4.0	51.0
L/S	1.4	0.4	0.8	2.1
Prey/Pred. ratio	0.96	0.41	0.30	2.00
Specialized Pred frac.	0.58	0.19	0.33	0.88
Gen	1.66	0.35	1.13	2.13
Vul	1.95	0.79	1.00	4.00
C	0.18	0.07	0.07	0.28
Cyclicity	1.38	0.65	0.00	2.59

Table 57: Summary statistics for proposed EIPs and IBSs

	Mean	Stan. Dev.	Min.	Max.
S	11.5	5.6	3.0	23.0
L	20.4	13.1	2.0	51.0
L/S	1.7	0.7	0.7	3.1
Prey/Pred. ratio	1.00	0.38	0.40	2
Specialized Pred frac.	0.49	0.26	0.18	1
Gen	2.04	0.63	1.00	3.125
Vul	2.20	0.73	1.00	3.5714
C	0.17	0.08	0.07	0.3906
Cyclicity	1.52	1.16	0.00	3.8737

6.3 Material Flows in Industrial Symbioses and Nature

The previous section quantifies structural similarities and differences between industrial symbioses and ecological networks. This section takes a further step by comparing steady-state material flow regimes in these two classes of networks. Using

Input-Output techniques developed to quantify material flows in industrial systems, this section analyzes a typical chemical complex design and a purportedly bio-inspired redesign. Then, it uses generated metrics to compare these systems with ecosystems.

6.3.1 Input-Output Analysis for Industrial Material Flows

Input-output (I-O) analysis quantifies the direct and indirect material flows between nodes of a network at a given moment. Analyses of this type allow one to quantify a number of network flow properties such as the fraction of cycled material. The following brief overview of I-O analysis draws from that of Bailey and uses a simple example to explicate the purpose of his mathematics (Bailey 2000, Bailey, et al. 2005).

The analysis begins with the representation of a network of flows as a Production matrix (**P**). Taking the diagramed network in Figure 47 as an example, one writes its production matrix as seen in Figure 48. The five types of variables in both figures are:

$\mathbf{H}_i \equiv$ Holons (nodes) i = 1, 2,…n

$f_{ij} \equiv$ Material flow rate from node j to node i

$x_i \equiv$ State variable indicating material storage (+ subscript) or retrieval (- subscript) rate for node i

$y_{0j} \equiv$ Material outflow rate from node j to beyond the network

$z_{i0} \equiv$ Material inflow rate from beyond the network to node i

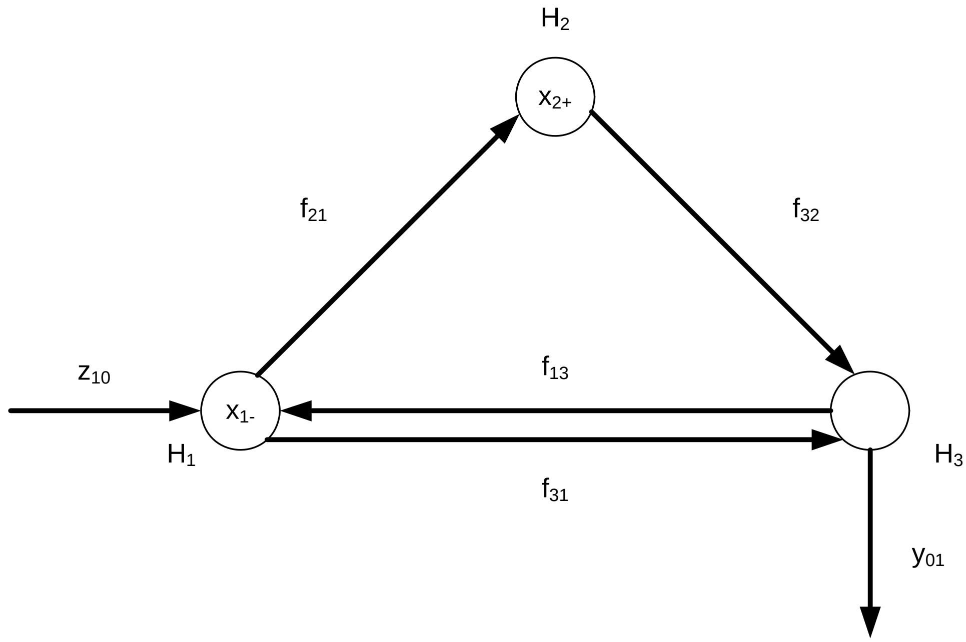


Figure 47: Example material flow network

$$
\begin{array}{cc}
 & \text{From} \\
 & \begin{array}{ccccccc} z_{10} & x_{1-} & H_1 & H_2 & H_3 & y_{03} & x_{2+} \end{array} \\
P = & \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
z_{10} & x_{1-} & 0 & 0 & f_{13} & 0 & 0 \\
0 & 0 & f_{21} & 0 & 0 & 0 & 0 \\
0 & 0 & f_{31} & f_{32} & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & y_{03} & 0 & 0 \\
0 & 0 & 0 & x_{2+} & 0 & 0 & 0
\end{bmatrix}
\begin{array}{c} z_{10} \\ x_{1-} \\ H_1 \\ H_2 \\ H_3 \\ y_{03} \\ x_{2+} \end{array}
\begin{array}{c} \\ \\ \\ \text{To} \\ \\ \\ \\ \end{array}
\end{array}
$$

Figure 48: Production matrix for example network

Representing the network as a production matrix provides immediate advantages as well as setting the stage for further mathematical development. Specifically, it gives ready access to system throughflow (TST), total inflow ($\sum IN$) and total outflow ($\sum OUT$). Where n is the total number of nodes in a network, total inflow rate is the sum of material input from outside the network and retrieved at each node, while total outflow sums flows leaving the network and material stored at nodes.

$$\sum IN = \sum_{i=1}^{n} z_{i0} - \sum_{i=1}^{n} x_{i-} \tag{14}$$

$$\sum OUT = \sum_{j=1}^{n} y_{0j} + \sum_{j=1}^{n} x_{j+} \tag{15}$$

In the example, one sees that $\sum IN = z_{10} - x_{1-}$ and $\sum OUT = y_{01} + x_{2+}$. Throughflow is defined as the rate of material passing through a node k, and system throughflow is the sum of each node's throughflow.

$$T_k = \sum_{j=1}^{n} f_{kj} + z_{k0} - x_{k-} \tag{16}$$

$$TST = \sum_{k=1}^{n} T_k \tag{17}$$

For the example, the sum of each nodes throughflow is $TST = f_{13} + f_{21} + f_{31} + f_{32} + z_{10} - x_{1-}$.

The next step transforms **P** into an instantaneous fractional inflow matrix $\mathbf{Q}^*$**.** One accomplishes this by dividing each P_{ij} element of **P** by the sum of each i-th row, which is equivalent to dividing the elements of each row by the rows' corresponding throughflow (T_k). In the cases where T_k is zero, the elements of the rows in question remain zero.

Creation of the transitive closure matrix, $\mathbf{N}^*$**,** marks the final step in the derivation for the purposes of this analysis. One arrives at this matrix by taking the inverse of the difference between an identity matrix and the network's instantaneous fractional inflow matrix.

$$\mathbf{N^{*}=(I-Q^{*})^{-1}} \tag{18}$$

Bailey presents the detailed mathematical reasoning behind this relationship (Bailey 2000).

Elements of **P** and **N** provide the information needed to calculate a number of metrics that quantify the flows in a network at a given moment. For the purposes of the following analyses, path length and Cycling Index (CI) are paramount. Mean path length, $\overline{PL}$, is the dividend of total system throughflow and total inflow. In an inflow analysis, it represents the average number of nodes visited by units of inflow before exiting the system.

$$\overline{PL} = \frac{TST}{\sum IN} \tag{19}$$

To calculate CI, one needs the total system throughflow that is cycled by the network (TST_c), and to determine TST_c, one needs the return cycling efficiency (RE_k) of each k node in the network. The diagonal elements of $\mathbf{N}^*$ provide the necessary information to calculate RE_k.

$$RE_k = \frac{n_{kk}^* - 1}{n_{kk}^*} \tag{20}$$

Since RE_k is the fraction of material cycled through a node, the amount of cycled flow for a node is the product of RE_k and throughflow, T_k. One obtains TST_c by summing this product for each node in the network.

$$TST_c = \sum_{i=1}^{n} RE_i T_i \tag{21}$$

The cycling index is the fraction of material cycled through the network; so, one obtains it by dividing cycled flow by total flow.

$$CI = \frac{TST_c}{TST} \tag{22}$$

Combining the ideas of path length and cycling provides metrics for the portion of $\overline{PL}$ resulting from cycled ($\overline{PL_c}$) and non-cycled ($\overline{PL}_s$) material flows.

$$\overline{PL}_c = \frac{TST_c}{\sum IN} \tag{23}$$

$$\overline{PL}_s = \frac{TST - TST_c}{\sum IN} \tag{24}$$

6.3.2 Lower Mississippi River Corridor

Singh and coauthors propose a redesign of an agro-chemical complex in the Lower Mississippi River Corridor guided by the general industrial ecology notion of "waste equals food" – especially in the case of CO_2 (Singh, et al. 2007). Their presentation of nearly complete mass balances for the original design and the redesign represents an ideal opportunity to observe the influence of imbuing industrial material flow networks with biological characteristics. This section presents summary material flow data and assumptions used during the I-O analysis of the original design and the purportedly bio-inspired redesign. Readers interested in the complexes' material flow structures should consult the source publication (Singh, et al. 2007).

Table 58 and Table 59 contain summary mass flow data for each facility in the two complexes. The inflow column provides the sum of bulk material flowing into each node from outside the complex and from other nodes. The outflow column sums the total bulk mass flow rate leaving each node for other nodes or areas beyond the complex boundary. The difference column calculates the difference between inflow and outflow rates.

Table 58: Plants, inflows and outflows for original Mississippi River Corridor agro-chemical complex

Plant	Inflow (Mt/yr)	Outflow (Mt/yr)	Difference (Mt/yr)
Sulfuric Acid Plant	15.7049	15.7049	0
Power gen.	6.4124	6.6141	-0.2017
Ammonia plant	1.4933	1.4932	1E-04
Ethylbenzene	0.8618	0.8618	0
Phosphoric acid plant	19.6718	19.6718	0
Nitric acid plant	1.0724	1.0723	1E-04
Urea plant	0.1673	0.1673	0
Methanol plant	0.1822	0.1822	0
Styrene	0.8618	0.8618	0
Ammonium Nitrate plant	0.3789	0.3789	0
Granular triple super phosphate	0.8832	0.8832	0
Mono & Di-ammonium phosphates granulation	2.8475	2.8475	0
UAN plant	0.0605	0.0605	0
Acetic acid	0.0094	0.0094	0

Since the designers present a system operating in steady state, inflows should balance outflows for each facility. The difference column indicates that this is true for almost all facilities in the complex. Power generation is an exception for both complexes; it exceeds the tolerable fourth decimal place variation. This difference is not explained by the authors, but it may represent addition of onsite cooling water. The I-O model represents the difference between inflow and outflow as a negative (negative subscript) state variable, making the generation facility a source for bulk material.

Table 59: Plants, inflows and outflows for redesigned Mississippi River Corridor agro-chemical complex

Plant	Inflow (Mt/yr)	Outflow (Mt/yr)	Difference (Mt/yr)
Sulfuric Acid Plant	15.7049	15.7049	0
Power gen.	5.8779	6.0424	-0.1645
Ammonia plant	1.5169	1.5169	0
Ethylbenzene	0.8619	0.8618	1E-04
Phosphoric acid plant	19.6718	19.6718	0
Nitric acid plant	1.0208	1.021	-0.0002
Urea plant	0.1636	0.1637	-1E-04
Methanol plant	0.1822	0.1822	0
Styrene	0.5224	0.5223	1E-04
Ammonium Nitrate plant	0.3608	0.3608	0
Granular triple super phosphate	0.8832	0.8832	0
Mono & Di-ammonium phosphates granulation	2.8475	2.8475	0
UAN plant	0.0605	0.0605	0
Acetic acid	0.0082	0.0082	0
Graphite and H2	0.1046	0.1046	0
Syngas	0.2072	0.2071	1E-04
Propene and H2	0.0438	0.0438	0
Propylene plant	0.0651	0.0651	0
Formic acid	0.0779	0.0779	0
Methylamines	0.0907	0.0906	0.0001
DME	0.0854	0.0854	0

6.3.3 I-O Analysis Results for Lower Mississippi River Corridor

Using the analysis outlined in Section 6.3.1 on the agro-chemical complex designs (Singh, et al. 2007), one generates the comparative material flow metric values in Table 60. Two striking features emerge by conducting this comparison. First, the magnitudes of these metrics remain almost the same despite the addition of seven facilities to the eco-industrial agro-chemical complex. Second, cycling path length and cycling index decrease for the redesign. Together, these results suggest that the design may have proved less successful and potentially less biological than its designers hoped.

Table 60: Input -Output metric values for the base and eco-industrial designs of the Lower Mississippi River Corridor agro-chemical complexes

I-O Metric	Agro-chemical complex	EIP Agro-chemical complex	Percent Difference
$\overline{PL}$	1.430744	1.4366	0.4%
$\overline{PL}_s$	1.424536	1.4333	0.6%
$\overline{PL}_c$	0.006209	0.0032	-48.1%
CI	0.004339	0.002244	-48.3%

Interestingly, the absolute magnitude of the flow metrics changed little as a result of the redesign. Addition of seven facilities to the original agro-chemical complex resulted in a percent difference increase in path length of < 1%. This increase came entirely in the form of non-cyclic path length and at the cost of a 48% drop in cyclic path length. The already low cycling index decreased by 48%! When one considers the position of the new plants in the redesigned complex's structure, the small increase in path length becomes less surprising. Most new plants are only one or two path lengths from raw material input to product and waste output.

The fall in cyclic path length and cycling index result from the loss of a benzene recycling loop between ethyl-benzene and styrene manufacture. The redesigned complex included a styrene plant that used less benzene; additional benzene leaves the system as product. In the eco-industrial version of the complex, the designers found a number of ways to use CO_2, but most of these involved bonding its elements with product or cascading it through the system, not cycling. Thus, the designers' efforts did not enhance material cycling at this scale by utilizing CO_2 emissions.

Viewed through a material flow lens, the redesign achieved little progress. The number of times input materials provided functional value (path length) hardly increased. This increase came at a cost of material reuse within the system. The designers' own comments about their evaluative life cycle inventory assessment echo this conclusion. They found that their successful effort to limit global warming emissions resulted in higher fossil fuel usage as well as greater human health and smog impacts (Singh, et al. 2007). Such results beg a question. Are biologically inspired flow regimes less useful for sustainable industrial network design than one might hope, or was the examined system less than biological?

6.3.4 Material Flow Compared

Comparing material flow metric values for the Mississippi Corridor agro-chemical complex with those found in ecosystems allows one to answer the question that closes the previous section. If the agro-chemical systems appear comparable to ecosystems, one gains support for the conclusion that ecologically based material flow regimes may not provide environmentally beneficial guidance for industrial resource network design. If the two systems prove less than comparable, one cannot attribute the weaknesses of the redesign noted in Section 6.3.3 to adherence to ecological forms. This later conclusion opens the way for speculation about the benefits of better matching network structures with ecological analogs.

Bailey's flow analysis (Bailey 2000) of ecosystems investigated by Finn (Finn 1977) provides the ecological data one needs for the comparison. Table 61 contains metric values for real ecosystems while Table 62 contains metric values for material flow models of general ecosystem types. Values for the two agro-chemical complex designs appear in both tables for comparative purposes.

Table 61: Material flow metric values for ecosystems investigated by Finn (Finn 1977, Bailey 2000)

Ecosystem	**PL**	**PL_s**	**PL_c**	**CI**
Cedar Bog Lake	1.15	1.15	0	0
Marine Coprography	1.45	1.27	0.18	0.12
Hubbard Brook	14.5	3.43	11.1	0.764
Agro-Chemical Complex	**PL**	**PL_s**	**PL_c**	**CI**
Original Design	1.4307	1.4245	0.0062	0.004339
Redesign as EIP	1.4366	1.4333	0.0032	0.002244

As the metric values in both tables clearly show, material flow regimes for the agro-chemical complexes have more in common with simple freshwater ecosystems such as Cedar Bog Lake and the general stream model. The simple ecosystems and the agro-chemical complex designs possess material transport regimes dominated by linear flows, as made evident by low PL_c and CI values for these systems. With comparatively low path lengths between 1 and 2, input material flows through one to two networks nodes and leaves the system.

Table 62: Material flow metric values for general models for different ecosystem types (Bailey 2000)

General Ecosystem Models	**PL**	**PL_s**	**PL_c**	**CI**
Stream	1.04	1.02	0.02	0.001
Lake	9.3	3.31	5.99	0.644
Temperate Forest	26.6	4.44	22.2	0.833
Ocean	34.4	4.73	29.7	0.862
Salt March	74.3	5.34	69.0	0.928
Tundra	223.0	5.39	217.6	0.976
Tropical Forest	210.2	4.75	205.4	0.979
Grassland	2091.0	5.89	2085.1	0.997
Agro-Chemical Complex	**PL**	**PL_s**	**PL_c**	**CI**
Original Design	1.4307	1.4245	0.0062	0.004339
Redesign as EIP	1.4366	1.4333	0.0032	0.002244

In contrast, the other ecosystems and general ecosystem models exhibit far longer path lengths and much greater cycling. The general grassland model possesses a total path length three orders of magnitude longer than the agro-chemical complex designs. Cycling index values range from 0.12 to 0.997, at least two orders of magnitude greater than that observed for agro-chemical complexes.

Material flow metric comparison reveals that the agro-chemical complex designs resemble simple, flow through ecosystems when viewed through the lens of material flow analysis. However, the complexes markedly differ from the majority of listed ecosystems and general ecosystem models. This outcome indicates that the agro-chemical complex redesign's material flow regime is far from the average flow regime that one might encounter in nature. This outcome also implies that adoption of a more biological flow regime remains a plausible, though not certain, means of reducing a resource networks environmental impact. Exploration of this plausible possibility is the topic of the next Section.

6.4 Bio-inspired Industrial Network Design

Prior sections noted environmental benefits, quantified structures and calculated flow metrics for industrial symbioses. Along the way, similarities and differences between industrial symbioses and ecosystems were noted. This section puts the bio-inspired guideline discussed in this chapter to the test. Here, the bio-inspired metric values used for comparative purposes become design goals for a carpet tile recycling network.

6.4.1 Carpet Flow Model

The basic carpet model used in Section 6.4 represents steady-state production, distribution and end-of-life carpet tile material flows. These flows connect a carpet tile producer, consumers, reuse centers, recycling centers and landfills servicing 13 counties in the metropolitan Atlanta region. Prior work by Guidry and Intlekofer coupled with the author's own knowledge of a leading carpet tile manufacturer's operations provide the basis for the model's structural assumptions and much of the data used to populate it (Guidry 2008, Intlekofer 2009).

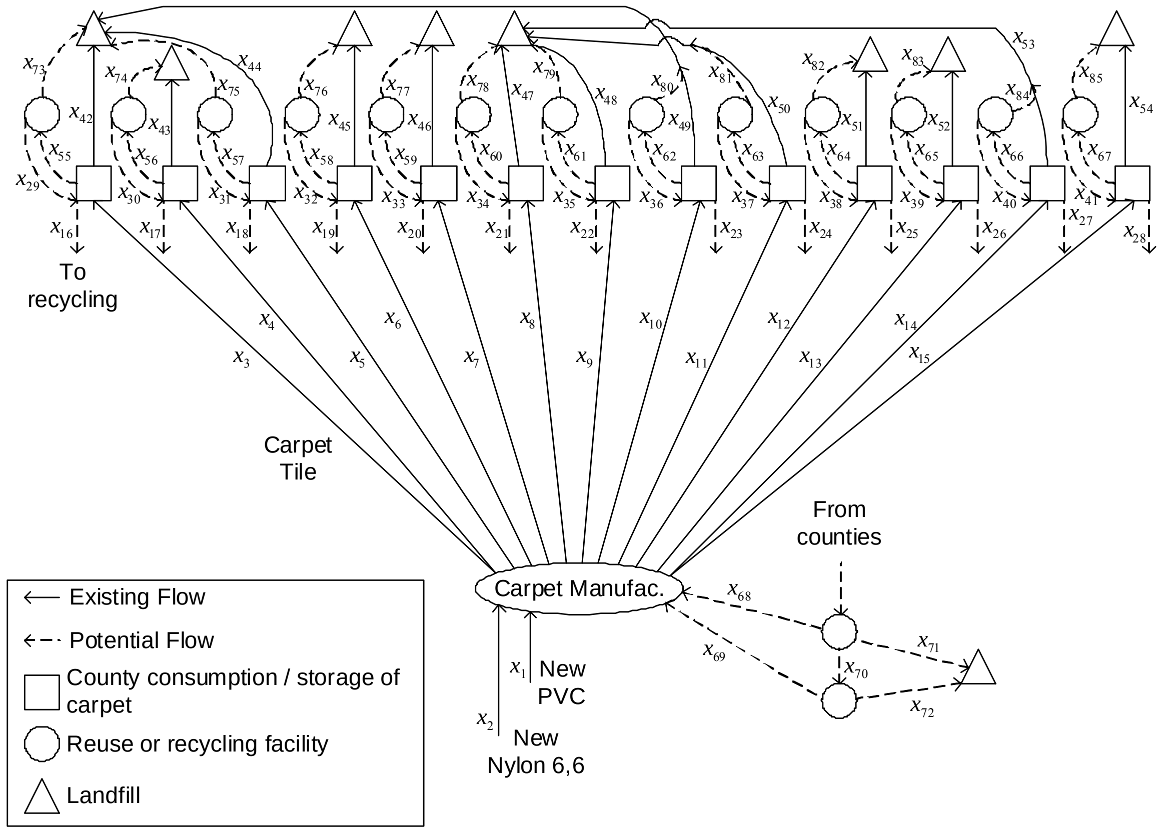


Figure 49: Model of existing and potential carpet tile and carpet tile material flows in metro-Atlanta region

Figure 49 contains a diagram of the carpet flow model's structure. Solid lines represent existing material and finished carpet flows while dashed ones represent potential flows. While not drawn to scale, each line represents a distance. For the existing structure, new PVC backing and Nylon 6,6 enter the carpet manufacturer where they become carpet tiles. Carpet tiles leave manufacturing and arrive at one of the Atlanta's 13 metropolitan counties, marked by squares in Figure 49. Carpet consumption occurs over a county's geographic area, but this model adopts Guidry's simplifying assumption that consumption occurs at each county's centrally located seat of government (Guidry 2008). New carpet displaces old carpet which is sent to one of eight landfills (triangles). Potential flows allow carpet tile reuse and recycling in each county. Instead of landfill disposal, one can decide to reuse some carpet or send it to recycling. The presence of these two choices at each of the 13 counties creates the model's 26 design variables. The circle nearest each square is a county's reuse / repurposing center. Carpet tile sent to a reuse center is cleaned and sent back to consumption in the county, reducing the need for new carpet. Carpet tile sent for recycling from each county arrives at the first circle in the lower right corner of the structural diagram. This circle contains the processes needed to separate the major carpet tile constituents (PVC backing and Nylon 6,6) and recycle PVC backing. Face material can be sent to the second circle in the lower right corner to recycle Nylon 6,6. This recycling facility is assumed to use the thermo-mechanical recycling process outlined by Intlekofer (Intlekofer 2009). Recycled PVC backing and Nylon 6,6 are then sent back to manufacturing where they reduce the need for new PVC and nylon.

Six types of equations quantify the network structure described in the preceding paragraph. First, a single equation relates input materials to carpet tile output by the manufacturer. Second, each node in the network is described by a steady state mass balance. Third, carpet consumption in each county is held constant and determined by county population (See Table 63) (Guidry 2008).

Table 63: 2008 population and annual carpet tile consumption estimates for metro-Atlanta counties

County	Population	Carpet Tile Consumption [kg/yr]	Nylon 6,6 and PVC backing in Tile [kg/yr]
Cherokee	141,903	167,351	128,861
Clayton	236,517	278,934	214,779
Cobb	607,751	716,745	551,893
Coweta	89,215	105,214	81,015
DeKalb	665,865	785,281	604,666
Douglass	92,174	503,804	387,929
Fayette	91,236	107,630	82,875
Forsyth	98,407	116,156	89,440
Fulton	816,006	962,348	741,008
Gwinnett	588,448	693,980	534,364
Henry	119,341	140,743	108,372
Paulding	81,678	96,326	74,171
Rockdale	70,111	82,684	63,667

Newly manufactured carpet tile and reused carpet tile satisfy this demand. The mass listed in the final column of Table 63 is the mass of PVC backing and Nylon 6,6, which constitutes ~77% of a carpet tile's mass (2009). Since this model only tracks PVC backing and Nylon 6,6, it is this mass that quantifies carpet tile demand in each county. The fourth set of equations provides efficiencies for the reuse / repurposing centers. In a similar way, the fifth set defines the overall efficiency of the PVC backing and Nylon 6,6 recycling facilities. A final equation dictates the amount of Nylon 6,6 sent to recycling after removal from each carpet tile. The baseline optimization formulation found in Section 6.4.2 contains a mathematical presentation of all six types of equations.

6.4.2 Conventional Optimization Model

Figure 50 presents a conventional baseline optimization model for manufacture, distribution, reuse and recycling of carpet tiles. It contains a complete list of cost, emission and other parameters used in the optimization as well as the material flow equations mentioned in Section 6.4.1. The flow equations relate 26 designer controlled flows of used carpet to reuse and recycling to the other 59 flows in the network. Other equations relate material flows to cost and emissions objectives or impose constraints on capacity and flow direction. The model is conventional in the sense that it optimizes the carpet flow network for costs and emissions.

Given

Parameters

Costs:

c_{pvc} = 0.2758	PVC backing (PVC and filler) cost [$/kg]
c_n=3.55	Nylon 6,6 cost [$/kg]
c_{gas}=.0369	Industrial cost of natural gas [$/kWh]
c_{tip}=0.03	Landfill tipping fee [$/kg]
c_d=0.61	EIA diesel fuel price estimate for Summer 2009 [$/L]
c_e=.0559	Retail electricity price [$/kWh]
c_{Lman}=13.78	Carpet tile manufacturing wage in 2008 [$/hr]
c_{Lt}=16.6	Hourly truck driver wage in 2008 [$/hr]
c_{Lru}=10.41	Reuse cleaning labor [$/hr]
c_{Lbale}=11.8	Baling labor [$/hr]
c_{Ls}=13.21	Shredding labor [$/hr]
c_{Lg}=13.21	Grinding labor [$/hr]
c_{Lms}=14.98	Material separation labor [$/hr]
c_{Lp}=13.78	PVC pellet creation labor [$/hr]
c_{Lncy}=13.5	Nylon cyclonic air separator labor [$/hr]
c_{Lnb}=13.5	Nylon bunker melt labor [$/hr]
c_{Lns}=13.5	Nylon spinneret [$/hr]
c_{Lnc}=13.5	Nylon cooling [$/hr]
c_{Lnd}=13.5	Nylon drawing [$/hr]
c_{Lnw}=13.5	Nylon winding [$/hr]

Emissions:

$\mathbf{e_{pvc}}$=[2015, 10.27, 0.0007, 12.12, 8.43, 0.001, 4.03, 0.002, 3E-05, 1.4, 1.47, 10.43]	g emission/kg PVC produced [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]
$\mathbf{e_n}$=[6681, 42.09, 0.74, 21.6, 17.85, 2E-06, 6.27, 0.08, 4E-06, 3.89, 2.11, 0]	g emission/kg Nylon 6,6 produced [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]
$\mathbf{e_{cleaner}}$=[7.28E-03, 0, 0, 4.78E-05, 8.94E-06, 0, 0, 0, 7.78E-11, 0, 0, 0]	g emission/kg deep cleaning solution produced [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs,

	Hg, HC, PM, SO_x]
$\mathbf{e_{v3}}$=[487.446; 0.0032; 0.0030; 0.0061; 3.06; 0; 11.87; 0; 0; 1.00; 0.08; 0]	g emission/km [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]
$\mathbf{e_{v8A}}$=[882.502; 0.0032; 0.0030; 0.011; 6.52; 0; 25.26; 0; 0; 2.12; 0.16; 0]	"
$\mathbf{e_e}$=[629.58; 0; 0; 4.13; 0.77; 0; 0; 0; 6.73E-06; 0; 0; 0]	g emission/kWh generated; only CO_2, SO_2, NO_x and Hg provided [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]
$\mathbf{e_{gas}}$=[181; 0; 0.00828; 0.0015; 0; 0; 0; 0; 0; 0; 0; 0]	g emission/kWh natural gas burned; only CO_2, N_2O, and SO_2 recorded [CO_2, CH_4, N_2O, SO_2, NO_x, Pb, CO, VOCs, Hg, HC, PM, SO_x]

Unit Efficiencies:

f_{pvc}=1, 0.76, 43	Total material efficiency for PVC recycling under ideal, expected and worst case scenarios (output PVC backing mass/input backing mass)
f_n=1, 0.76, 43	Total material efficiency for Nylon 6,6 recycling under ideal, expected and worst case scenarios (output nylon face mass/input nylon face mass)
R_n=1	Fraction of carpet tile face mass sent to nylon recycling
f_{17}=0.9	Total material efficiency for carpet reuse (output reusable carpet tile mass/input reusable carpet tile mass)
f_{18}=0.9	"
f_{19}=0.9	"
f_{20}=0.9	"
f_{21}=0.9	"
f_{22}=0.9	"
f_{23}=0.9	"
f_{24}=0.9	"
f_{25}=0.9	"
f_{26}=0.9	"
f_{27}=0.9	"
f_{28}=0.9	"
f_{29}=0.9	"

Carpet Tile Manufacturing Process Data:

e_{man}=0.2079	Electricity consumed while making carpet tiles [kWh/kg]
L_{man}=0.0734	Labor required to make carpet tiles [hr/kg]
s_{man}=0.3160	Natural gas consumed to make carpet tiles [kWh/kg]

Recycling Process Data:

$e_{ruclean}$=1.16E-5	Electricity consumed while cleaning reusable carpet tiles [kWh/kg]
e_{bale}=0.002	Electricity consumed to bale recyclable carpet tiles [kWh/kg]

e_s=0.056	Electricity consumed to shred recyclable carpet tiles [kWh/kg]
e_g=0.055	Electricity consumed to grind recyclable carpet tiles [kWh/kg]
e_{ms}=0.178	Electricity consumed to separate ground carpet tile materials [kWh/kg]
e_p=0.01	Electricity consumed during PVC pellet creation [kWh/kg]
e_{ncy}=0.0082	Electricity consumed to cyclonically separate nylon [kWh/kg]
e_{nb}=0.819	Electricity consumed by a bunker melter [kWh/kg]
e_{ns}=0.506	Electricity consumed by nylon spinnerets [kWh/kg]
e_{nc}=0.232	Electricity consumed to cool nylon [kWh/kg]
e_{nd}=0.317	Electricity consumed to draw nylon [kWh/kg]
e_{nw}=0.257	Electricity consumed to wind drawn nylon [kWh/kg]
T_{ru}=1.16E-5	Throughflow for cleaning reusable carpet tiles [kg/hr]
T_{bale}=0.002	Throughflow for baling recyclable carpet tiles [kg/hr]
T_s=0.056	Throughflow for shredding recyclable carpet tiles [kg/hr]
T_g=0.055	Throughflow for grinding recyclable carpet tiles [kg/hr]
T_{ms}=0.178	Throughflow for separating ground carpet tile materials [kg/hr]
T_p=0.01	Throughflow for PVC pellet creation [kg/hr]
T_{ncy}=.0082	Throughflow for cyclonic nylon separation [kg/hr]
T_{nb}=0.819	Throughflow for bunker melter [kg/hr]
T_{ns}=0.506	Throughflow for nylon spinnerets [kg/hr]
T_{nc}=0.232	Throughflow for cooling nylon [kg/hr]
T_{nd}=0.317	Throughflow for nylon draw [kg/hr]
T_{nw}=0.317	Throughflow for nylon winding [kg/hr]
Transportation Data:	
s_{avg}=93.115	Average truck speed in km/hr (55 mph)
l_{v3}=1814	Load capacity of a HDDV3 truck [kg/truck]
l_{v8A}=12247	Load capacity of a HDDV8A truck [kg/truck]
η_{v3}=.425	Fuel efficiency of a HDDV3 truck [km/L]
η_{v8A}= η_{v3}	Fuel efficiency of a HDDV8A truck [km/L]

Constants

d=[0, 0, 166, 100, 134, 50, 121, 103, 84, 172, 108, 159, 134, 146, 138, 166, 100, 134, 50, 121, 103, 84, 172, 108, 159, 134, 146, 138, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 21, 11, 56, 8, 19, 34, 63, 31, 8, 21, 29, 48, 11, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 634, 634, 12.1, 12.1, 21, 11, 56, 8, 19, 34, 63, 31, 8, 21, 29, 48, 11]	Distances [km] between network nodes such as county seats, landfills, carpet manufacturing, recycling and reuse
r=[167351.9, 278934, 716745.2, 105214.9, 785281.4, 503804, 107630.1, 116156.4, 962348, 693980.4, 140743.7, 96326.15, 82684.7]	Carpet tile consumption for 13 counties in metro-Atlanta region [kg/yr]

Relevant Equations

Network Material Flows :

$x_1 + x_2 + x_{68} + x_{69} - x_3 - x_4 - x_5 - x_6 - x_7 - x_8 - x_9 - x_{10} - x_{11} - x_{12} - x_{13} - x_{14} - x_{15} = 0$	Carpet manufacturing plant mass balance
$x_3 + x_{55} - x_{16} - x_{29} - x_{42} = 0$	Steady-state mass carpet tile mass balances
$x_4 + x_{56} - x_{17} - x_{30} - x_{43} = 0$	"
$x_5 + x_{57} - x_{18} - x_{31} - x_{44} = 0$	"
$x_6 + x_{58} - x_{19} - x_{32} - x_{45} = 0$	"
$x_7 + x_{59} - x_{20} - x_{33} - x_{46} = 0$	"
$x_8 + x_{60} - x_{21} - x_{34} - x_{47} = 0$	"
$x_9 + x_{61} - x_{22} - x_{35} - x_{48} = 0$	"
$x_{10} + x_{62} - x_{23} - x_{36} - x_{49} = 0$	"
$x_{11} + x_{63} - x_{24} - x_{37} - x_{50} = 0$	"
$x_{12} + x_{64} - x_{25} - x_{38} - x_{51} = 0$	"
$x_{13} + x_{65} - x_{26} - x_{39} - x_{52} = 0$	"
$x_{14} + x_{66} - x_{27} - x_{40} - x_{53} = 0$	"
$x_{15} + x_{67} - x_{28} - x_{41} - x_{54} = 0$	"
$x_{29} - x_{55} - x_{73} = 0$	Reuse / Repurposing center mass balances
$x_{30} - x_{56} - x_{74} = 0$	"
$x_{31} - x_{57} - x_{75} = 0$	"
$x_{32} - x_{58} - x_{76} = 0$	"
$x_{33} - x_{59} - x_{77} = 0$	"
$x_{34} - x_{60} - x_{78} = 0$	"
$x_{35} - x_{61} - x_{79} = 0$	"
$x_{36} - x_{62} - x_{80} = 0$	"
$x_{37} - x_{63} - x_{81} = 0$	"
$x_{38} - x_{64} - x_{82} = 0$	"
$x_{39} - x_{65} - x_{83} = 0$	"
$x_{40} - x_{66} - x_{84} = 0$	"
$x_{41} - x_{67} - x_{85} = 0$	"
$x_{16} + x_{17} + x_{18} + x_{19} + x_{20} + x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + x_{26} + x_{27} + x_{28} - x_{68} - x_{70} - x_{71} = 0$	PVC recycling plant mass balance
$x_{70} - x_{69} - x_{72} = 0$	Nylon recycling plant mass balance
$x_3 + x_{55} = 128861$	Carpet tile consumption for metro-Atlanta counties
$x_4 + x_{56} = 214779$	"
$x_5 + x_{57} = 551893$	"
$x_6 + x_{58} = 81015$	"
$x_7 + x_{59} = 604666$	"

$x_8 + x_{60} = 387929$	"
$x_9 + x_{61} = 82875$	"
$x_{10} + x_{62} = 89440$	"
$x_{11} + x_{63} = 741008$	"
$x_{12} + x_{64} = 534464$	"
$x_{13} + x_{65} = 108372$	"
$x_{14} + x_{66} = 74171$	"
$x_{15} + x_{67} = 63667$	"
$x_{55} - f_{17}x_{29} = 0$	Reuse facility material efficiencies
$x_{56} - f_{18}x_{30} = 0$	"
$x_{57} - f_{19}x_{31} = 0$	"
$x_{58} - f_{20}x_{32} = 0$	"
$x_{59} - f_{21}x_{33} = 0$	"
$x_{60} - f_{22}x_{34} = 0$	"
$x_{61} - f_{23}x_{35} = 0$	"
$x_{62} - f_{24}x_{36} = 0$	"
$x_{63} - f_{25}x_{37} = 0$	"
$x_{64} - f_{26}x_{38} = 0$	"
$x_{65} - f_{27}x_{39} = 0$	"
$x_{66} - f_{28}x_{40} = 0$	"
$x_{67} - f_{29}x_{41} = 0$	"
$x_{68} - 0.792f_{pvc}(x_{16} + x_{17} + x_{18} + x_{19} + x_{20} + x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + x_{26} + x_{27} + x_{28}) = 0$	Carpet recycling efficiency for PVC
$x_{70} - 0.208R_n(x_{16} + x_{17} + x_{18} + x_{19} + x_{20} + x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + x_{26} + x_{27} + x_{28}) = 0$	Recovered nylon
$x_{69} - f_n x_{70} = 0$	Carpet recycling efficiency for Nylon 6,6
$x_2 + x_{69} - 0.208(x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15}) = 0$	Carpet tile composition equation

Costs :

$C_{mat} = c_{pvc}x_1 + c_n x_2$	Cost of PVC backing and nylon
$C_{man} = \left(c_e e_{man} + c_{Lman}L_{man} + c_{gas}s_{man}\right)\sum_{i=3}^{15} x_i$	Cost of manufacturing carpet tiles
$C_{tip} = c_{tip}\left(\sum_{i=42}^{54} x_i + \sum_{i=73}^{85} x_i\right)$	Tipping fees for carpet tile sent to landfill

$$C_t = \left[\frac{8\left(\sum_{i=1}^{68} x_i d_i + \sum_{i=71}^{85} x_i\, d_i\right)}{3l_{v3}}\right]\left[\left(\frac{c_d}{\eta_{v3}}\right) + \left(\frac{c_{Lt}}{s_{avg}}\right)\right] + \left[\frac{2\left(\sum_{i=69}^{70} x_i d_i\right)}{l_{v8A}}\right]\left[\left(\frac{c_d}{\eta_{v8A}}\right) + \left(\frac{c_{Lt}}{s_{avg}}\right)\right]$$ Transport costs

$$C_{ruclean} = \left(c_e e_{ruclean} + \frac{c_{Lru}}{T_{ru}}\right)\left(\sum_{i=29}^{41} x_i\right)$$ Cost of cleaning at reuse facility

$$C_{bale} = \left(c_e e_{bale} + \frac{c_{Lbale}}{T_{bale}}\right)\sum_{i=16}^{28} x_i$$ Cost of baling

$$C_s = \left(c_e e_s + \frac{c_{Ls}}{T_s}\right)\sum_{i=16}^{28} x_i$$ Cost of shredding

$$C_g = \left(c_e e_g + \frac{c_{Lg}}{T_g}\right)\sum_{i=16}^{28} x_i$$ Cost of grinding

$$C_{ms} = \left(c_e e_{ms} + \frac{c_{Lms}}{T_{ms}}\right)\sum_{i=16}^{28} x_i$$ Cost of material separation

$$C_p = \left(c_e e_p + \frac{c_{Lp}}{T_p}\right) x_{68}$$ Cost of PVC pellet creation

$$C_{ncy} = \left(c_e e_{ncy} + \frac{c_{Lncy}}{T_{ncy}}\right) x_{70}$$ Cost of Nylon 6,6 cyclonic air separation

$$C_{nb} = \left(c_e e_{nb} + \frac{c_{Lnb}}{T_{nb}}\right) x_{70}$$ Cost of Nylon 6,6 bunker melting

$$C_{ns} = \left(c_e e_{ns} + \frac{c_{Lns}}{T_{ns}}\right) x_{70}$$ Cost of Nylon 6,6 spinning

$$C_{nc} = \left(c_e e_{nc} + \frac{c_{Lnc}}{T_{nc}}\right) x_{70}$$ Cost of Nylon 6,6 cooling

$$C_{nd} = \left(c_e e_{nb} + \frac{c_{Lnd}}{T_{nd}}\right) x_{70}$$ Cost of Nylon 6,6 drawing

$$C_{nw} = \left(c_e e_{nw} + \frac{c_{Lnw}}{T_{nw}}\right) x_{70}$$ Cost of Nylon 6,6 winding

$$C = C_{mat} + C_{man} + C_{tip} + C_t + C_{ruclean} + C_{bale} + C_s + C_g + C_{ms} + C_p + C_{ncy} + C_{nb} + C_{ns} + C_{nc} + C_{nd} + C_{nw} = 0$$ Total cost

Emissions :

$\boldsymbol{e}_{mat} = \boldsymbol{e}_{pvc}x_1 + \boldsymbol{e}_n x_2$	Emissions from production of PVC backing and nylon
$\boldsymbol{e}_{mf} = \left(\boldsymbol{e}_e e_{man} + \boldsymbol{e}_{gas} s_{man}\right) \sum_{i=3}^{15} x_i$	Carpet tile manufacturing emissions
$\boldsymbol{e}_t = \left[\frac{8\left(\sum_{i=1}^{68} x_i d_i + \sum_{i=71}^{85} x_i\, d_i\right)}{3 l_{v3}}\right] \boldsymbol{e}_{v3} + \left[\frac{2\left(\sum_{i=69}^{70} x_i d_i\right)}{l_{v8A}}\right] \boldsymbol{e}_{v8A}$	Transport emissions
$\boldsymbol{e}_{ruclean} = \left(\boldsymbol{e}_{cleaner} + \boldsymbol{e}_e e_{ruclean}\right) \sum_{i=29}^{41} x_i$	Reuse emissions
$\boldsymbol{e}_{bale} = \boldsymbol{e}_e e_{bale} \sum_{i=16}^{28} x_i$	Baling emissions
$\boldsymbol{e}_s = \boldsymbol{e}_e e_s \sum_{i=16}^{28} x_i$	Shredding emissions
$\boldsymbol{e}_g = \boldsymbol{e}_e e_g \sum_{i=16}^{28} x_i$	Grinding emissions
$\boldsymbol{e}_{ms} = \boldsymbol{e}_e e_{ms} \sum_{i=16}^{28} x_i$	Material separation emissions
$\boldsymbol{e}_p = \boldsymbol{e}_e e_p x_{68}$	PVC pellet creation emissions
$\boldsymbol{e}_{ncy} = \boldsymbol{e}_e e_{ncy} x_{70}$	Nylon 6,6 cyclonic air separation emissions
$\boldsymbol{e}_{nb} = \boldsymbol{e}_e e_{nb} x_{70}$	Nylon 6,6 bunker melter emissions
$\boldsymbol{e}_{ns} = \boldsymbol{e}_e e_{ns} x_{70}$	Nylon 6,6 spinneret emissions
$\boldsymbol{e}_{nc} = \boldsymbol{e}_e e_{nc} x_{70}$	Nylon 6,6 cooling emissions
$\boldsymbol{e}_{nd} = \boldsymbol{e}_e e_{nd} x_{70}$	Nylon 6,6 drawing emissions
$\boldsymbol{e}_{nw} = \boldsymbol{e}_e e_{nw} x_{70}$	Nylon 6,6 winding emissions
$\boldsymbol{e} = \boldsymbol{e}_{mat} + \boldsymbol{e}_{mf} + \boldsymbol{e}_t + \boldsymbol{e}_{ruclean} + \boldsymbol{e}_{bale} + \boldsymbol{e}_s + \boldsymbol{e}_g + \boldsymbol{e}_{ms} + \boldsymbol{e}_p + \boldsymbol{e}_{ncy} + \boldsymbol{e}_{nb} + \boldsymbol{e}_{ns} + \boldsymbol{e}_{nc} + \boldsymbol{e}_{nd} + \boldsymbol{e}_{nw}$	Total emissions

Find:

x_i for i=16,17…41	Amount of used carpeting sent to recycling (i=16-28) and reuse (i=29-41) centers

Satisfy:

$\sum_{i=16}^{28} x_i \leq 915{,}761$	PVC recycling facility capacity constraint
$x_{i+28} \leq 0.1 r_i\, , for\ i = 1{,}2 \ldots 13$	Reuse facility capacity constraint
$x_i \geq 0\, , for\ i = 1{,}2 \ldots 85$	Positive flow constraint

Minimize:

C	Total costs

e Total emissions

Figure 50: Baseline optimization model of costs and emissions associated with carpet manufacture, distribution, reuse and recycling

The formulation allows one to vary design variables representing the amount of used carpet sent to reuse or recycling. Each of the 13 modeled counties generates waste carpet that goes to landfill, reuse or recycling. At each county seat, carpet sent to reuse and carpet sent to recycling are independent variables in the model. Having two independent variables in 13 counties creates the model's 26 design variables.

Costs divide into three categories: material, labor and energy. Since it focuses on PVC backing and Nylon 6,6, the costs of these two carpet tile components account for the entire material cost. Tile manufacturing, transport, reuse preparation and the various recycling processes incur labor and energy costs.

Material consumption and energy use generate emissions. Emissions associated with new PVC backing and Nylon 6,6 represent the emissions caused by the creation of these plastics from raw materials. The model's representation of carpet manufacturing assumes 100% material efficiency; so, only energy consumption in the forms of natural gas and electricity account for the emissions generated during production. Carpet tiles, PVC backing and Nylon 6,6 sent to landfill are assumed to be inert and incapable of releasing emissions. Energy consumption in the form of diesel fuel and electricity generates emissions during transport and recycling, respectively.

Constraints on the model include capacity limits for reuse and recycling as well as flow direction constraints. Capacity constraints reflect the reality that carpet reclamation is a new activity for the textile industry that lacks the infrastructure needed to absorb the available used carpet resource. In the case of reuse, a capacity constraint additionally accounts for the fact that carpet tile replacement can occur on an individual basis.

Piecemeal replacement of worn tiles decreases the likelihood of recovering reusable carpet tiles. Flow direction constraints prevent mathematically possible though physically meaningless solutions such as flow from PVC recycling directly to carpet consumption.

6.4.3 Bio-Inspired Optimization Model

Figure 51 presents a bio-inspired baseline optimization model for manufacture, distribution, reuse and recycling of carpet tiles. It contains a complete list of efficiency parameters and physical constants used in the optimization as well as the material flow equations which form the core of the model. Equations relate material flows to objectives; other equations impose constraints on capacity and flow direction. The bio-inspired model differs with the conventional model in that it seeks to minimize and maximize structural and flow regime metrics customarily used to analyze food webs.

Given

Parameters

Unit Efficiencies:

f_{pvc}=1, 0.76, 43	Total material efficiency for PVC recycling under ideal, expected and worst case scenarios (output PVC backing mass/input backing mass)
f_n=1, 0.76, 43	Total material efficiency for Nylon 6,6 recycling under ideal, expected and worst case scenarios (output nylon face mass/input nylon face mass)
R_n=1	Fraction of carpet tile face mass sent to nylon recycling
f_{17}=0.9	Total material efficiency for carpet reuse (output reusable carpet tile mass/input reusable carpet tile mass)
f_{18}=0.9	“
f_{19}=0.9	“
f_{20}=0.9	“
f_{21}=0.9	“
f_{22}=0.9	“
f_{23}=0.9	“
f_{24}=0.9	“
f_{25}=0.9	“
f_{26}=0.9	“
f_{27}=0.9	“

$f_{28}=0.9$	"
$f_{29}=0.9$	"

Constants

r=[167351.9, 278934, 716745.2, 105214.9, 785281.4, 503804, 107630.1, 116156.4, 962348, 693980.4, 140743.7, 96326.15, 82684.7]	Carpet tile consumption for 13 counties in metro-Atlanta region [kg/yr]

Relevant Equations

Network Material Flows :

$x_1 + x_2 + x_{68} + x_{69} - x_3 - x_4 - x_5 - x_6 - x_7 - x_8 - x_9 - x_{10} - x_{11} - x_{12} - x_{13} - x_{14} - x_{15} = 0$	Carpet manufacturing plant mass balance
$x_3 + x_{55} - x_{16} - x_{29} - x_{42} = 0$	Steady-state mass carpet tile mass balances
$x_4 + x_{56} - x_{17} - x_{30} - x_{43} = 0$	"
$x_5 + x_{57} - x_{18} - x_{31} - x_{44} = 0$	"
$x_6 + x_{58} - x_{19} - x_{32} - x_{45} = 0$	"
$x_7 + x_{59} - x_{20} - x_{33} - x_{46} = 0$	"
$x_8 + x_{60} - x_{21} - x_{34} - x_{47} = 0$	"
$x_9 + x_{61} - x_{22} - x_{35} - x_{48} = 0$	"
$x_{10} + x_{62} - x_{23} - x_{36} - x_{49} = 0$	"
$x_{11} + x_{63} - x_{24} - x_{37} - x_{50} = 0$	"
$x_{12} + x_{64} - x_{25} - x_{38} - x_{51} = 0$	"
$x_{13} + x_{65} - x_{26} - x_{39} - x_{52} = 0$	"
$x_{14} + x_{66} - x_{27} - x_{40} - x_{53} = 0$	"
$x_{15} + x_{67} - x_{28} - x_{41} - x_{54} = 0$	"
$x_{29} - x_{55} - x_{73} = 0$	Reuse / Repurposing center mass balances
$x_{30} - x_{56} - x_{74} = 0$	"
$x_{31} - x_{57} - x_{75} = 0$	"
$x_{32} - x_{58} - x_{76} = 0$	"
$x_{33} - x_{59} - x_{77} = 0$	"
$x_{34} - x_{60} - x_{78} = 0$	"
$x_{35} - x_{61} - x_{79} = 0$	"
$x_{36} - x_{62} - x_{80} = 0$	"
$x_{37} - x_{63} - x_{81} = 0$	"
$x_{38} - x_{64} - x_{82} = 0$	"
$x_{39} - x_{65} - x_{83} = 0$	"
$x_{40} - x_{66} - x_{84} = 0$	"
$x_{41} - x_{67} - x_{85} = 0$	"
$x_{16} + x_{17} + x_{18} + x_{19} + x_{20} + x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + x_{26} + x_{27} + x_{28} - x_{68} - x_{70} - x_{71} = 0$	PVC recycling plant mass balance

$x_{70} - x_{69} - x_{72} = 0$	Nylon recycling plant mass balance
$x_3 + x_{55} = 128861$	Carpet tile consumption for metro-Atlanta counties
$x_4 + x_{56} = 214779$	"
$x_5 + x_{57} = 551893$	"
$x_6 + x_{58} = 81015$	"
$x_7 + x_{59} = 604666$	"
$x_8 + x_{60} = 387929$	"
$x_9 + x_{61} = 82875$	"
$x_{10} + x_{62} = 89440$	"
$x_{11} + x_{63} = 741008$	"
$x_{12} + x_{64} = 534464$	"
$x_{13} + x_{65} = 108372$	"
$x_{14} + x_{66} = 74171$	"
$x_{15} + x_{67} = 63667$	"
$x_{55} - f_{17}x_{29} = 0$	Reuse facility material efficiencies
$x_{56} - f_{18}x_{30} = 0$	"
$x_{57} - f_{19}x_{31} = 0$	"
$x_{58} - f_{20}x_{32} = 0$	"
$x_{59} - f_{21}x_{33} = 0$	"
$x_{60} - f_{22}x_{34} = 0$	"
$x_{61} - f_{23}x_{35} = 0$	"
$x_{62} - f_{24}x_{36} = 0$	"
$x_{63} - f_{25}x_{37} = 0$	"
$x_{64} - f_{26}x_{38} = 0$	"
$x_{65} - f_{27}x_{39} = 0$	"
$x_{66} - f_{28}x_{40} = 0$	"
$x_{67} - f_{29}x_{41} = 0$	"
$x_{68} - 0.792 f_{pvc}(x_{16} + x_{17} + x_{18} + x_{19} + x_{20} + x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + x_{26} + x_{27} + x_{28}) = 0$	Carpet recycling efficiency for PVC
$x_{70} - 0.208(x_{16} + x_{17} + x_{18} + x_{19} + x_{20} + x_{21} + x_{22} + x_{23} + x_{24} + x_{25} + x_{26} + x_{27} + x_{28}) = 0$	Recovered nylon
$x_{69} - f_n x_{70} = 0$	Carpet recycling efficiency for Nylon 6,6
$x_2 + x_{69} - 0.208(x_3 + x_4 + x_5 + x_6 + x_7 + x_8 + x_9 + x_{10} + x_{11} + x_{12} + x_{13} + x_{14} + x_{15}) = 0$	Carpet tile composition equation
$m_{in} = x_1 + x_2$	Carpet material inflow

$$m_{tst} = \sum_{i=1}^{m}\sum_{j=1}^{n} p_{ij}$$ Total system throughflow

Input-Output Matrices and Vectors :

$\boldsymbol{P} = f(\boldsymbol{x})$ I-O Production matrix with nonzero elements determined by the structure of carpet flow network

$\boldsymbol{p}_{rsum} = \sum_{j=2}^{30} p_{ij}$ Column vector containing the sum of the elements of selected rows in matrix **P**

$$\boldsymbol{Q} = [q_{ij}] \; where \; q_{ij} = \begin{cases} \frac{p_{ij}}{\sum_{j=1}^{n} p_{ij}} for \; \sum_{j=1}^{n} p_{ij} > 0 \\ 0 \qquad for \; \sum_{j=1}^{n} p_{ij} \leq 0 \end{cases}$$ Instantaneous Fractional Flow matrix

$\boldsymbol{N} = (\boldsymbol{I} - \boldsymbol{Q})^{-1}$ Transitive Closure matrix

$\boldsymbol{c}_{re} = \left[\frac{n_{kk} - 1}{n_{kk}}\right] for \; k = 2,3 \dots 30$ Column vector of return cycling efficiencies for network nodes

$m_{tstc} = \boldsymbol{c}_{re}{}^{\boldsymbol{T}} \boldsymbol{p}_{\boldsymbol{rsum}}$ Cyclic throughflow

Adjacency and Community Matrices :

$\boldsymbol{A}_{\boldsymbol{adj}} = f(\boldsymbol{f})$ Structural adjacency matrix with binary elements determined by network connections

$\boldsymbol{C} = \boldsymbol{A}_{\boldsymbol{adj}}{}^{\boldsymbol{T}}$ Community matrix

Nodes, Trophic Links, Prey, and Predators :

$s = f(\boldsymbol{C}) = f(\boldsymbol{A}_{\boldsymbol{adj}})$ Number of nodes in a community matrix; usually equal to the size of the community matrix

$L = \sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}$ Number of links connected nodes in the adjacency or community matrix

$n_{prey} = \sum_{i=1}^{m} c_{row}(i)$ where $c_{row}(i) = \begin{cases} 1 \; for \sum_{j=1}^{n} c_{ij} > 0 \\ 0 \; for \sum_{j=1}^{n} c_{ij} = 0 \end{cases}$ Number of prey; the number of nonzero rows in the community matrix

$n_{predator} = \sum_{j=1}^{n} c_{col}(j)$ where $c_{col}(j) = \begin{cases} 1 \; for \sum_{i=1}^{m} c_{ij} > 0 \\ 0 \; for \sum_{i=1}^{m} c_{ij} = 0 \end{cases}$ Number of predators; the number of nonzero columns in the community matrix

$n_{s-pred} = \sum_{j=1}^{n} c_{scol}(j)$ where $c_{scol}(j) = \begin{cases} 1 \; for \sum_{i=1}^{m} c_{ij} = 1 \\ 0 \; for \sum_{i=1}^{m} c_{ij} \neq 1 \end{cases}$ — Number of specialized predators; the number of columns with a sum of one in the community matrix

Structural Metrics :

$L_d = L/_S$ — Link density

$c_{con} = L/_{S^2}$ — Connectance

$p_{special} = {}^{n_{s-pred}}/_{n_{predator}}$ — Specialized predator ratio

$p_r = {}^{n_{prey}}/_{n_{predator}}$ — Prey to predator ratio

$g = L/_{n_{predator}}$ — Generalization

$v = L/_{n_{prey}}$ — Vulernability

$\lambda = max. real\ eigenvalue\ \boldsymbol{A_{adj}}$ — Cyclicity

Input-Output Metrics :

$p_L = \dfrac{m_{tst}}{m_{in}}$ — Mean Path Length

$CI = \dfrac{m_{tstc}}{m_{tst}}$ — Cycling Index

$p_{LC} = \dfrac{m_{tstc}}{m_{in}}$ — Mean Cyclic Path Length

Find:

x_i for i=16,17…41 — Amount of used carpeting sent to recycling (i=16-28) and reuse (i=29-41) centers

Satisfy:

$\sum_{i=16}^{28} x_i \leq 915{,}761$ — PVC recycling facility capacity constraint

$x_{i+28} \leq 0.1 r_i \, , for\ i = 1{,}2 \ldots 13$ — Reuse facility capacity constraint

$x_i \geq 0 \, , for\ i = 1{,}2 \ldots 85$ — Positive flow constraint

Minimize:

$p_{special}, p_r$

Maximize:

$L_d, c_{con}, g,\ v,\ \lambda, p_L, CI$

Figure 51: Baseline optimization model of a bio-inspired network for carpet manufacture, distribution, reuse and recycling

Similar to the conventional model, the bio-inspired formulation allows one to vary design variables representing the amount of used carpet sent to reuse or recycling. Each of the 13 modeled counties generates waste carpet that goes to landfill, reuse or recycling.

At each county seat, carpet sent to reuse and carpet sent to recycling are independent variables in the model. Having two independent variables in 13 counties creates the model's 26 design variables.

Each set of design variables produces corresponding flow and network configurations which one uses to calculate bio-inspired metrics. These metrics quantify network structure and flow pattern. As previously stated, metrics such as specialized predator ratio ($p_{special}$), predator to prey ratio (p_r), link density (L_d), connectance (c_{con}), generalization (g), vulnerability (v) and cyclicity (λ) quantify network structure from an ecological perspective. Path length (p_L) and cycling index (CI) quantify network flows from an ecological perspective. When compared to linear flow industrial systems, one generally seeks to minimize $p_{special}$ and p_r while maximizing the other objectives (See Figure 46). However, the MATLAB representation of the bio-inspired baseline model uses goal values for each of these metrics taken from ecology and industrial ecology references (Briand 1983, Briand, et al. 1987, Hardy 2001, Fath 2007, Fath, et al. 2007). The goals are approached from above in the case of minimization and from below in the case of maximization.

Constraints on the model include capacity limits for reuse and recycling as well as flow direction constraints. Capacity constraints reflect the reality that carpet reclamation is a new activity for the textile industry that lacks the infrastructure needed to absorb the available used carpet resource. In the case of reuse, a capacity constraint additionally accounts for the fact that carpet tile replacement can occur on an individual basis. Piecemeal replacement of worn tiles decreases the likelihood of recovering reusable carpet tiles. Flow direction constraints prevent mathematically possible though physically meaningless solutions such as flow from PVC recycling directly to carpet consumption.

6.4.4 Optimal Network Configurations

Optimization of the models presented in Sections 6.4.2 and 6.4.3 met with mixed results. Solution of the linear traditional model proceeded to a defensible optimum, but the bio-inspired model's non-linear, mixed-integer solution space proved more than a match for available optimization algorithms. A stochastic search used in lieu of formal optimization found a desirable design for the bio-inspired problem. Comparison of the resulting designs revealed some differences and multiple similarities.

Constrained linear optimization of the traditional model with equally weighted goals was performed using MATLAB's "fmincon" solver. Ten feasible and infeasible starting points served as initial guesses for the algorithm (See Table 64). Table 65 contains design vectors selected by fmincon for each of the ten starting points. The algorithm proved sensitive to the initial guess, generating multiple "optimal" network configurations. As discussed and illustrated in Section 6.4.5, solution space flatness is the likely cause of this sensitivity. Four start points led to a configuration in which only reuse occurs while six others led to a mixture of reuse and recycling. Of the latter six, four equivalent solutions obtained by starting at configurations two, five, seven and ten minimized the traditional objective function (Z_{trad}) with a value of 0.1987. This solution rests against the 14 reuse and recycling capacity constraints, lending credence to its claim to optimality.

Table 64: Initial design vectors for optimization algorithm (kg/yr)

Design Var. (kg/yr)	Initial Points									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
x_{16} =	0	70443	0	70443	35222	0	0	1000	0	70443
x_{17}	0	70443	0	70443	35222	0	0	1000	305252	70443
x_{18}	0	70443	0	70443	35222	0	0	1000	0	70443
x_{19}	0	70443	0	70443	35222	0	0	1000	305252	70443
x_{20}	0	70443	0	70443	35222	0	457880	1000	0	70443
x_{21}	0	70443	0	70443	35222	0	0	1000	0	70443
x_{22}	0	70443	0	0	35222	35222	0	1000	305252	70443
x_{23}	0	70443	0	0	35222	35222	0	1000	0	70443
x_{24}	0	70443	0	0	35222	35222	457880	1000	0	70443
x_{25}	0	70443	0	0	35222	35222	0	1000	0	70443
x_{26}	0	70443	0	0	35222	35222	0	1000	0	70443
x_{27}	0	70443	0	0	35222	35222	0	1000	0	70443
x_{28}	0	70443	0	0	35222	35222	0	1000	0	70443
x_{29}	0	0	12886	12886	6443	6443	0	1000	0	12886
x_{30}	0	0	21478	21478	10739	0	0	1000	0	21478
x_{31}	0	0	55189	55189	27595	0	0	1000	0	55189
x_{32}	0	0	8102	8102	4051	0	0	1000	0	8102
x_{33}	0	0	60467	60467	30233	0	0	1000	0	60467
x_{34}	0	0	38793	38793	19396	0	0	1000	0	38793
x_{35}	0	0	8288	0	4144	0	0	1000	0	8288
x_{36}	0	0	8944	0	4472	4472	0	1000	0	8944
x_{37}	0	0	74101	0	37050	37050	0	1000	0	74101
x_{38}	0	0	53436	0	26718	26718	0	1000	0	53436
x_{39}	0	0	10837	0	5419	5419	0	1000	0	10837
x_{40}	0	0	7417	0	3709	3709	0	1000	0	7417
x_{41}	0	0	6367	0	3183	3183	0	1000	0	6367

Table 65: Traditional model's design vectors (optimal vectors shaded) and resultant objective function values obtained at different starting points

Design Var. (kg/yr)	Obtained Designs by Initial Point									
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
x_{16} =	0	0	0	70443	0	0	1	0	0	0
x_{17}	0	0	0	70443	1	0	0	0	0	8
x_{18}	0	419122	0	70443	419117	0	419104	0	0	419115
x_{19}	0	72914	0	70443	72914	0	72914	0	0	72914
x_{20}	0	0	0	70443	0	0	0	0	0	0
x_{21}	0	349136	0	70443	349136	0	349136	0	0	349136
x_{22}	0	74588	0	0	74588	35222	74588	0	0	74588
x_{23}	0	0	0	0	0	35222	0	0	0	0
x_{24}	0	0	0	0	2	35222	5	0	0	0
x_{25}	0	0	0	0	0	35222	6	0	0	0
x_{26}	0	0	0	0	2	35222	7	0	0	0
x_{27}	0	0	0	0	2	35222	0	0	0	0
x_{28}	0	0	0	0	0	35222	0	0	0	0
x_{29}	12886	12886	12886	12886	12886	6443	12886	12886	12886	12886
x_{30}	21478	21478	21478	21478	21478	0	21478	21478	21478	21478
x_{31}	55189	55189	55189	55189	55189	0	55189	55189	55189	55189
x_{32}	8102	8102	8102	8102	8102	0	8102	8102	8102	8102
x_{33}	60467	60467	60467	60467	60467	0	60467	60467	60467	60467
x_{34}	38793	38793	38793	38793	38793	0	38793	38793	38793	38793
x_{35}	8288	8288	8288	0	8288	0	8288	8288	8288	8288
x_{36}	8944	8944	8944	0	8944	4472	8944	8944	8944	8944
x_{37}	74101	74101	74101	0	74101	37050	74101	74101	74101	74101
x_{38}	53436	53436	53436	0	53436	26718	53436	53436	53436	53436
x_{39}	10837	10837	10837	0	10837	5419	10837	10837	10837	10837
x_{40}	7417	7417	7417	0	7417	3709	7417	7417	7417	7417
x_{41}	6367	6367	6367	0	6367	3183	6367	6367	6367	6367
Objective Function Values										
Z_{trad}	0.3788	0.1987	0.3788	0.3432	0.1987	0.3897	0.1987	0.3788	0.3788	0.1987
Z_{bio}	0.5246	0.4063	0.5246	0.4615	0.3997	0.4737	0.3997	0.5246	0.5246	0.3997

Attempts to optimize the bio-inspired model met with little success. MATLAB's gradient based "fmincon" and genetic algorithm based "ga" failed to find optimal network configurations. Consultations with Dr. Craig Tovey, an optimization expert in Georgia Institute of Technology's School of Industrial Systems Engineering, revealed that identification of a satisfactory optimum for all of the goals present in the problem's non-linear, mixed-integer objective function may not be possible. He suggested optimizing the network for a subset of these goals. However, the network design problem exists to compare as ecological a network as reasonable with a traditional one; so, optimization for a subset of the available ecological goals is unsatisfactory. Instead of sacrificing the ecological character of the objective function, a stochastic search algorithm found a good, though not optimal, configuration using all of the goals listed in Figure 51. The algorithm randomly generated 100,000 feasible points and selected one that minimized the value of an objective function composed of equally weighted bio-inspired network metrics. Table 66 lists the design variable and objective function values for this superior point.

Table 66: Best bio-inspired network configuration as identified by stochastic search

Design Variables and Values. (kg/yr)	
x_{16} =	29267
x_{17}	169226
x_{18}	180420
x_{19}	73343
x_{20}	7192
x_{21}	97875
x_{22}	15460
x_{23}	19003
x_{24}	135701
x_{25}	60064
x_{26}	80988
x_{27}	35038
x_{28}	11307
x_{29}	9946
x_{30}	19016
x_{31}	48666
x_{32}	5798
x_{33}	59870
x_{34}	28561
x_{35}	3674
x_{36}	6192
x_{37}	66717
x_{38}	48902
x_{39}	5139
x_{40}	4465
x_{41}	6094
Objective Function Values	
Z_{trad}	0.2155
Z_{bio}	0.3564

Comparing the optimum traditional point with a good point for the bio-inspired model reveals both differences and similarities. Starting with the objective function values (Z_{trad} and Z_{bio}), one sees that the optimum traditional point minimizes both. The bio-inspired point is not at the traditional model's minimum, but it is comparatively low. In fact, data in Table 65 and Table 66 suggest that the value of both objective functions might correlate. The traditional point makes maximum use of available recycling (915,761 kg/yr) and reuse (366,305 kg/yr) capacity; it uses all 13 possible reuse links.

With 914,883 kg/yr recycled, the bio-inspired point almost achieves maximum recycling capacity, and it also uses all available reuse links. The major difference between the two solutions is the number of recycling paths. The bio-inspired point makes use of all 13, but the traditional optimum configuration uses recyclable carpet from only four counties: Cobb, Cowetta, Douglass and Fayette. Optimization based on traditional goals selects counties based on proximity to landfills and the recycling center in LaGrange. The county seats of Cowetta and Fayette fall closest to LaGrange while those of Cobb and Douglass are comparatively far from landfills (See Table 67). Sending carpet to recycling from these counties avoids costs and emissions incurred by sending carpet from more distant ones or by sending it to distant landfills.

Table 67: Distance from metro-Atlanta counties to LaGrange and landfills

County	Distance to LaGrange [km]	Distance to Landfill [km]
Cherokee	166	21
Clayton	100	11
Cobb	134	56
Coweta	50	8
DeKalb	121	19
Douglass	103	34
Fayette	84	63
Forsyth	172	31
Fulton	108	8
Gwinnett	159	21
Henry	134	29
Paulding	146	48
Rockdale	138	11

In contrast, the bio-inspired objective function ignores distance. The utilized ecological metrics consider network structure and material flow regime, not the resistance to flow represented by the distance between two points. Introducing ecologically based metrics that account for the cost of "finding food" might push the bio-inspired results into closer alignment with the traditional ones. On the other hand, the current bio-inspired point may contain a certain degree of inherent network robustness not found in the traditional configuration. Cutting one of the traditional optimum's four recycling links is more likely to cause serious performance degradation than cutting one of the bio-inspired point's 13.

6.4.5 Design and Solution Space Exploration

Given the techniques used in Section 6.4.4, further design and solution space exploration is needed to support claims about the correspondence between traditional and bio-inspired network configurations. Direct visualization of a 26 dimensional design space is not possible for creatures accustomed to the four dimensions of space and time. Thankfully, aggregation of design dimensions and solution space exploration gives insight into the carpet model's high dimensional space. This insight confirms the reasonableness of the optimum network configurations found in the Section 6.4.4.

Though composed of 26 design variables, one can reduce the problem without drastically changing the fundamental choices about carpet tile recycling and reuse present in the model. Instead of choosing 13 recycling and 13 reuse carpet tile flows, one can compress the choice to two variables by varying the total amount of tile recycled and reused. Even division of the total amount over each group of 13 design variables while respecting capacity and flow direction constraints accomplishes this using the same models exercised for the purposes of optimization. The surfaces in Figure 52 to Figure 57 display the result of this aggregation. In these plots, the surface point closest to the reader is the point of maximum carpet tile recycling and reuse. The plots indicate that this point minimizes (falls closest to the desired goals) the objective functions for the traditional and bio-inspired models. Comparison of the three presented plot pairs for different levels of recycling efficiency shows that this relationship persists even when efficiency decays. One should note that the bio-inspired surface point at maximum recycling and zero reuse is a local minimum.

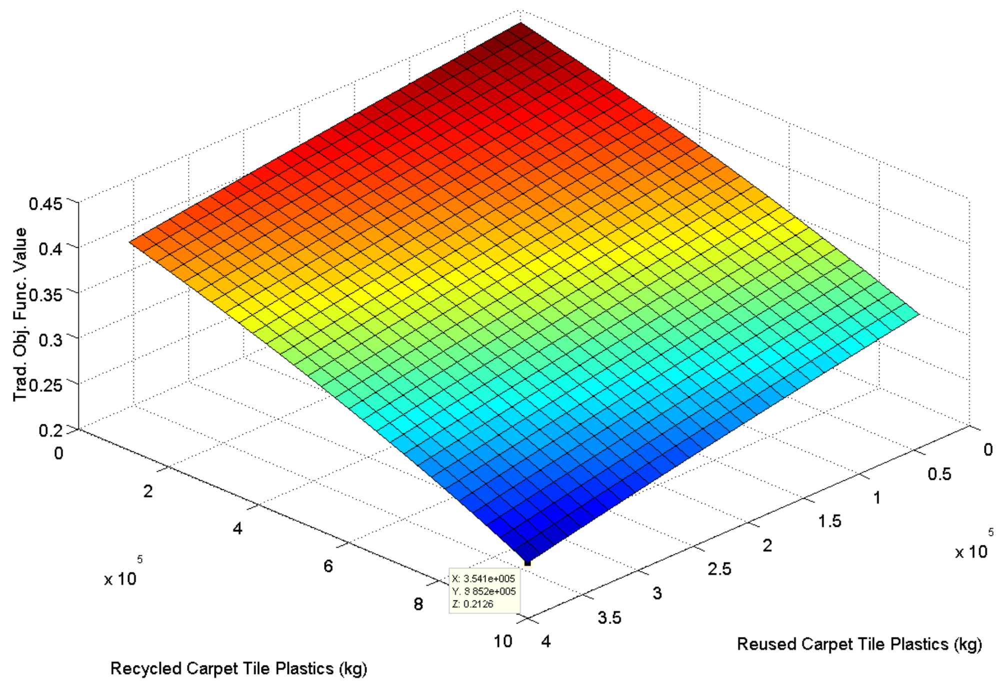


Figure 52: Traditional objective function value vs. recycled and reused mass (100% recycling efficiency)

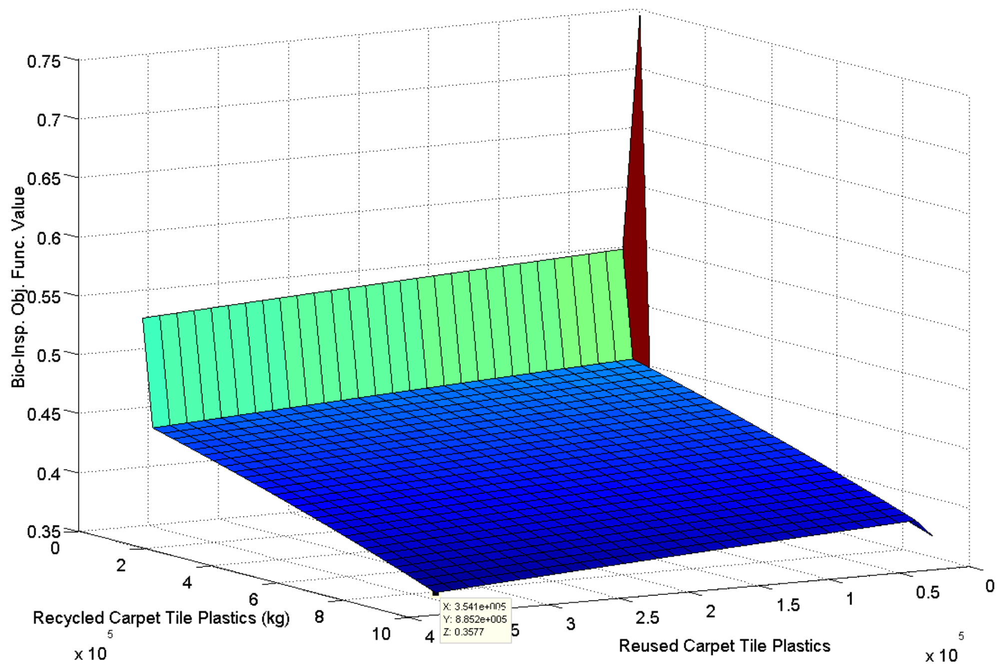


Figure 53: Bio-inspired objective function value vs. recycled and reused mass (100% recycling efficiency)

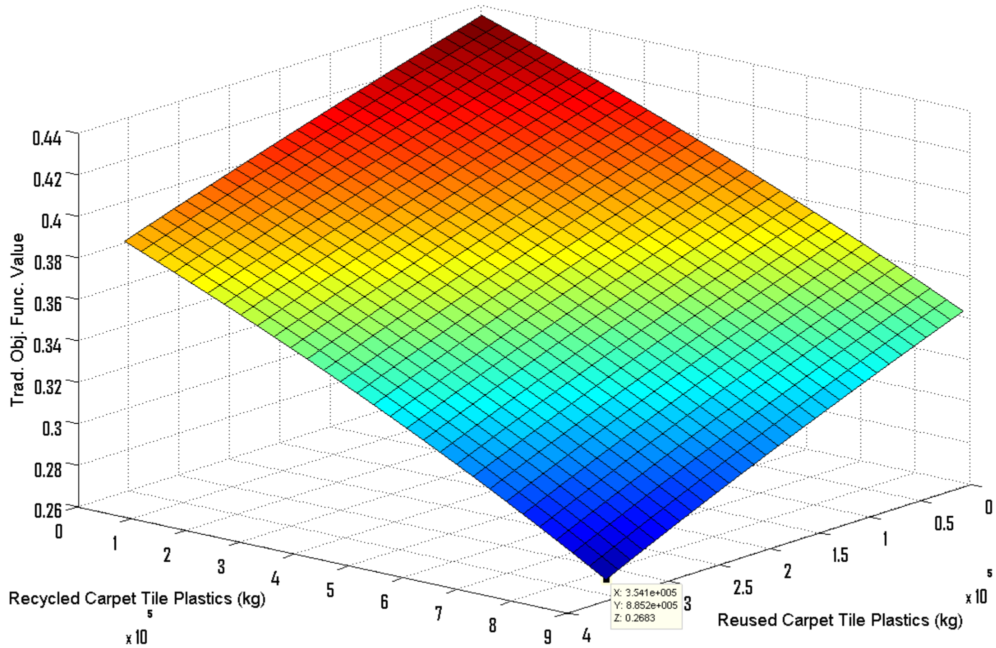


Figure 54: Traditional objective function value vs. recycled and reused mass (75% recycling efficiency)

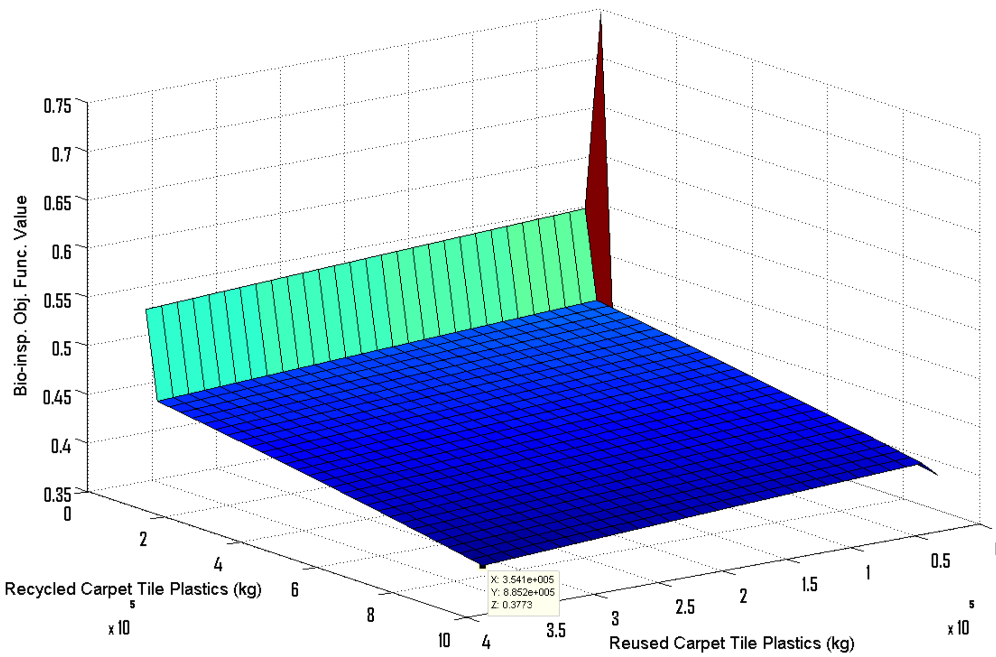


Figure 55: Bio-inspired objective function value vs. recycled and reused mass (75% recycling efficiency)

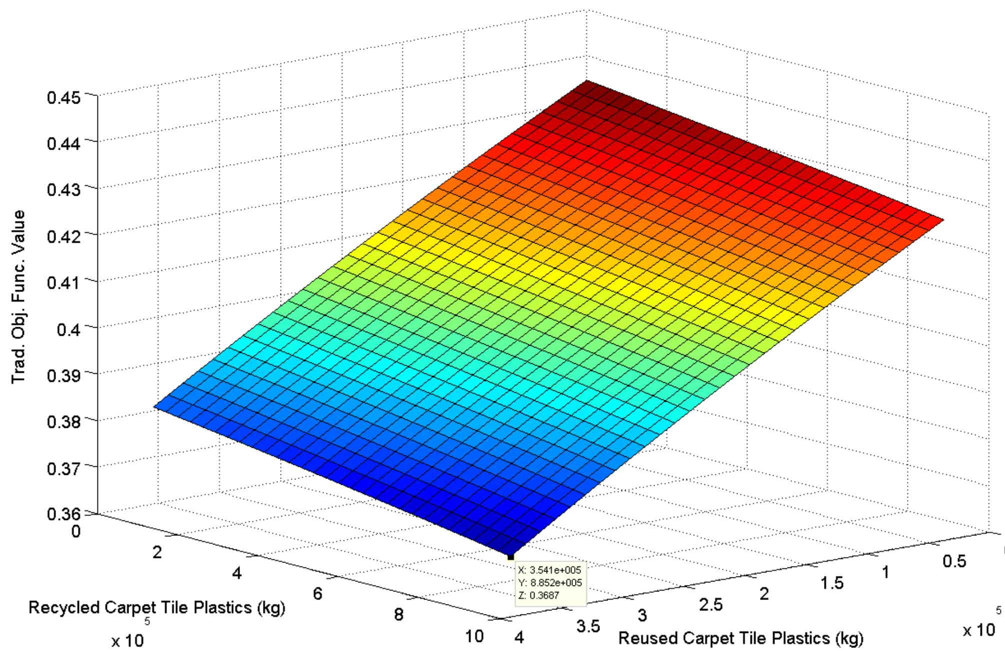


Figure 56: Traditional objective function value vs. recycled and reused mass (20% recycling efficiency)

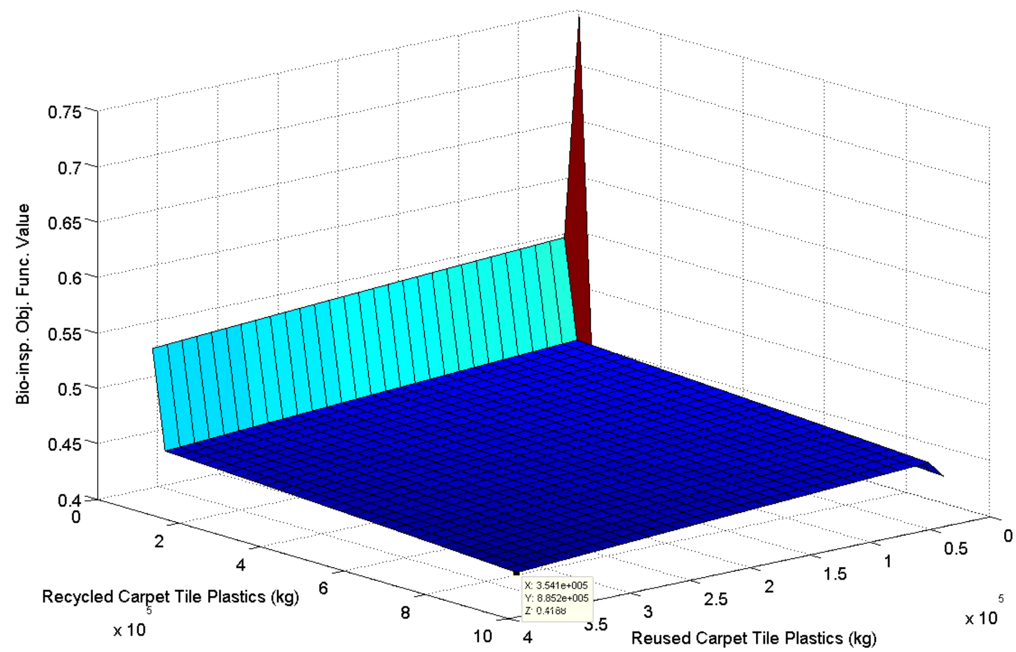


Figure 57: Bio-inspired objective function value vs. recycled and reused mass (20% recycling efficiency)

In Figure 53, Figure 55 and Figure 57, one observes comparatively sharp changes in the bio-inspired objective function's values near zero recycling and reuse. Such discontinuous behavior results from discontinuities in biological structural metrics. Structural metrics deactivate when flows reach ~0 and activate for flow values >0. Such behavior represents a problem when comparing bio-inspired and traditional model results using the technique that produced the previous six surfaces. The bio-inspired surfaces only present one of many possible network configurations.

One approach to the problem of multiple network configurations is to test for a correlation between traditional and bio-inspired objective function values for many randomly generated design configurations. Figure 58, Figure 59 and Figure 60 present the results of such tests. Each figure plots the traditional objective function value against that of the bio-inspired objective function for randomly generated design vectors. As one clearly sees, the two sets of values correlate regardless of recycling efficiency. However, the correlation degrades from a R^2 of 0.96 at 100% recycling efficiency to a R^2 of 0.74 at 20% recycling efficiency. This degradation is a consequence of the strong structural component of the bio-inspired objective function. Poor efficiency does not affect network structure; so, the bio-inspired objective function suffers less as it declines, decreasing the correlation. Nevertheless, network design configurations that minimize the bio-inspired objective function by meeting desirable ecological metric levels also minimize traditional costs and emissions.

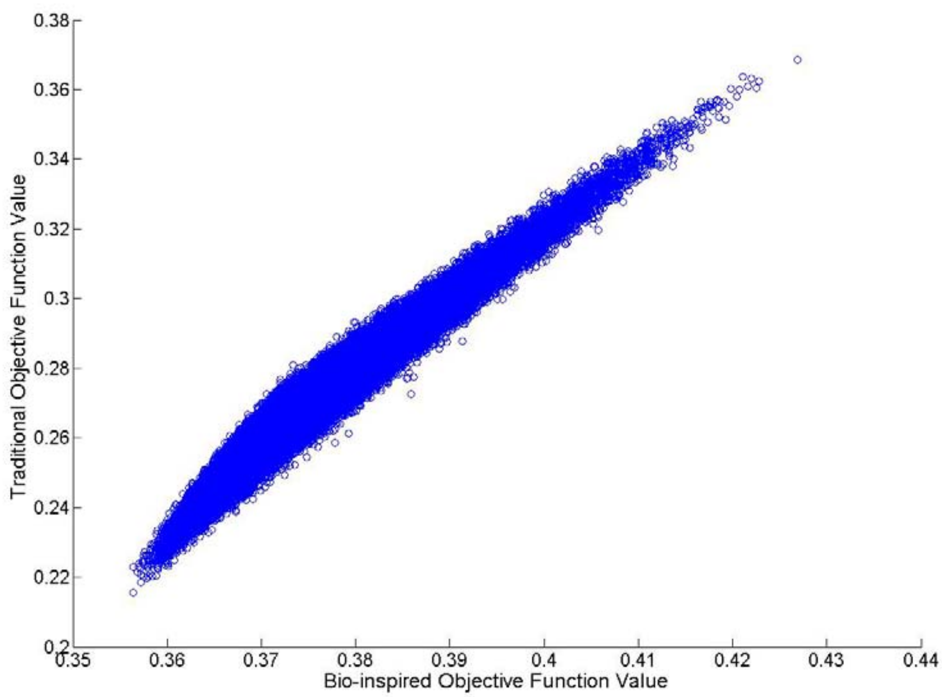


Figure 58: Traditional vs. Bio-inspired objective function values for 100,000 random network designs at 100% recycling efficiency (R^2=0.96)

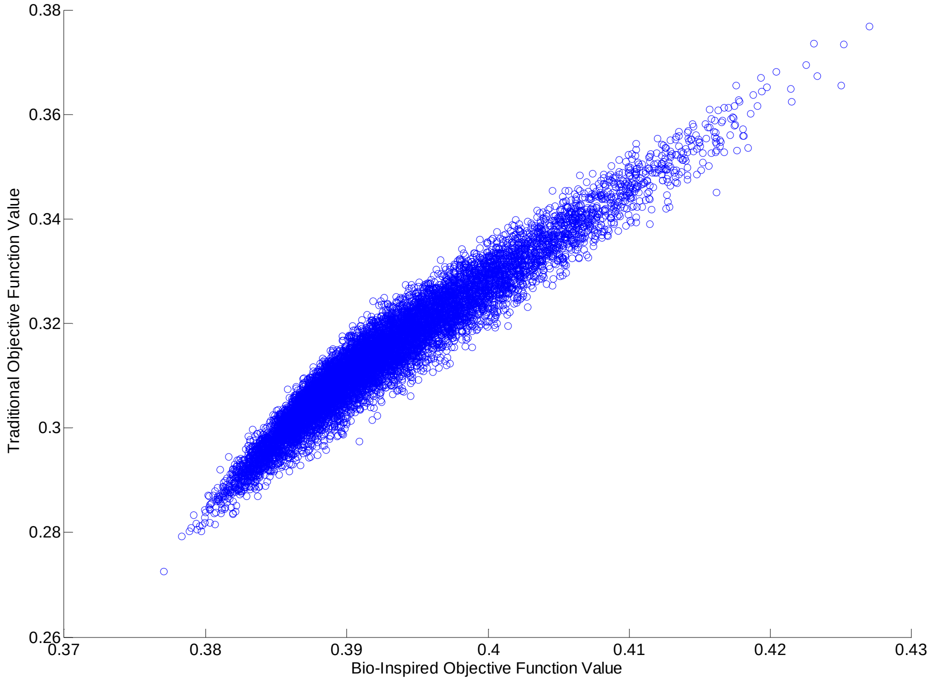


Figure 59: Traditional vs. Bio-inspired objective function value for 10,000 random network designs at 75% Recycling Efficiency (R^2=0.93)

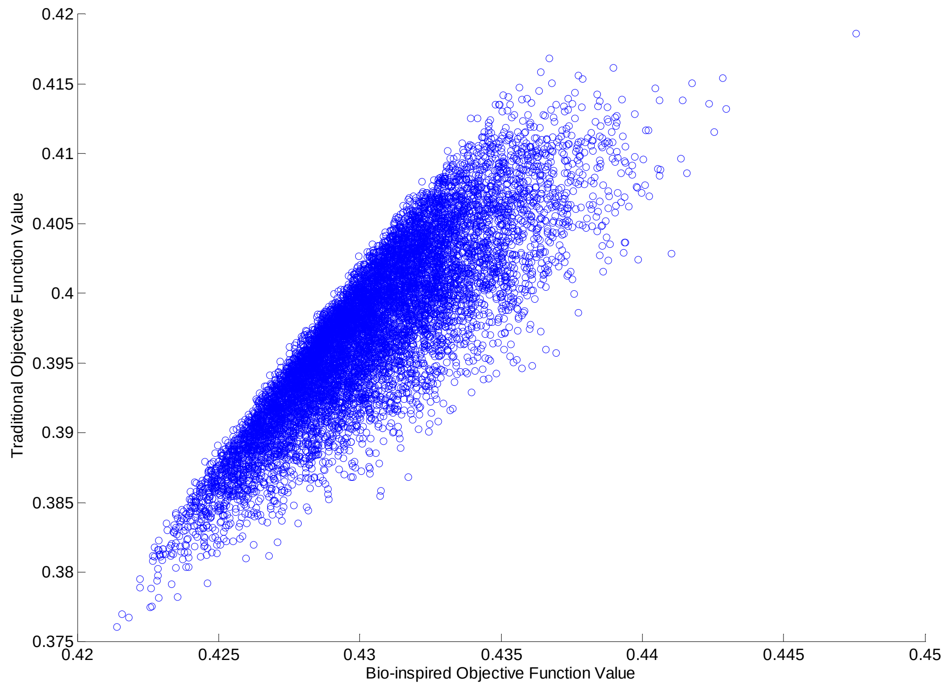


Figure 60: Traditional vs. Bio-inspired objective function value for 10,000 random network designs at 20% recycling efficiency (R^2=0.74)

The data presented in this section illustrate the behavior of the traditional and bio-inspired models in response to aggregated design inputs. A second set of tests reveal a positive correlation between the two objective functions. Taken together, design and solution space exploration findings support and clarify results obtained through optimization. Moreover, they provide further evidence that a biologically preferred network configuration is desirable from the traditional cost and emissions perspective.

6.5 Benefits of Bio-Inspired Patterns in Industrial Networks

By evaluating the environmental efficacy of imbuing industrial resource distribution networks with biological / ecological properties, this chapter provides information needed to answer the two primary questions asked in Chapter 1 at a larger organizational scale. Specifically, one discovers whether implementing ecological patterns in industrial networks leads to environmentally preferable configurations. And, one learns if bio-inspired measures, metrics and indicators facilitate this implementation.

A review of industrial symbioses in Section 6.1 reveals that even efforts to qualitatively adopt ecological structures in industrial resource networks can lead to improved environmental performance. The statistical tests and metric by metric comparisons in Section 6.2 indicate that symbioses are not the structural equivalent of ecological networks. However, those results also show that symbioses fall between "take, make, waste" linear systems and those observed in nature. A quantitatively discernable shift toward the ecological resulted in improved environmental performance. The outcome of the carpet recycling network design problem in Section 6.4 reinforces this finding. Networks with desirable configurations from a bio-inspired perspective also minimize life cycle costs and emissions.

Ecological metrics allow one to discern the difference between linear production systems, symbioses and ecological networks in Section 6.2. In Section 6.3, small changes in bio-inspired metrics mirror the limited life cycle inventory improvements observed for the redesign of a petrochemical plant. Analysis using bio-inspired metrics reveals the weakness of only using qualitative ecological guidance in this case, knowledge provided at a lower information cost than that required for a complete LCI. Section 6.4 holds the strongest evidence for the value of bio-inspired metrics. For the carpet recycling problem, bio-inspired metrics serve as the goals in an objective function that correlates with an objective function based on traditional cost and emissions goals.

Chapter 6 examines the dissertation's overarching proposition at the systems level. Taken together, presented evidence suggests that industrial resource networks imbued with ecological properties demonstrate superior environmental performance. Furthermore, use of ecological and bio-inspired metrics as network goals aids in identifying and designing environmentally preferable network architectures.

CHAPTER 7: REFLECTIONS UPON THE CONSTRUCTION OF HOLISTIC BIOMIMICRY

Chapter 7 brings closure to this dissertation by summarizing hypothesis development, listing contributions, identifying limitations and noting possible future research and development opportunities.

7.1 Hypotheses Revisited

Chapter 1 begins with a question and associated hypothesis concerning bio-inspiration's place in environmentally benign design and manufacturing (EBDM). Introducing the term holistic biomimicry, it advances the idea that a governing set of living system principles could serve as guides for EBDM. Partitioning this overarching hypothesis to facilitate investigation leads to two primary questions and hypotheses.

1. Biology literature detailing the inherent properties of living systems contains principles responsible for the biosphere's sustainability.

2. Existing and new measures, metrics and indicators derived from life's principles will provide the necessary translation between biology and engineering.

Discovering some of the principles underpinning the biosphere's inherent sustainability and learning to translate and apply them in an engineering context serve as the dissertation's primary objectives. This section exists to review the degree to which this work achieves these two objectives.

7.1.1 Principle Discovery

Principle discovery principally occurs in Chapter 3. Chapter 2 motivates Chapter 3's exploration by detailing the faults and failings of life cycle assessment, the most widely accepted current tool used to support EBDM. But, it is in the third chapter where Constant Comparative Method (CCM) finds principles in the sampled biology and ecology literature. From a list of ten extracted principles, an initial review cuts the set to six. A process involving comparison with existing EBDM guidelines and, importantly, review by a panel of biologists reduces the number of principles selected for further development and validation to three. In the end, the process produces principles. One can trace the roots of these characteristics of life to multiple bioscience publications and can take comfort in the knowledge that each withstood the scrutiny of review by biologists. While a claim to a complete set of principles is not possible, it is reasonable to state that each of the remaining three contain valuable lessons for those interested in environmental sustainability. Living systems principles with bearing on the biosphere's inherent environmental sustainability emerged as hypothesized.

7.1.2 EBDM Guideline Translation and Application

The second hypothesis in Chapter 1 contains an explicit and an implicit educated guess. Explicitly, the hypothesis states that measures, metrics and indicators can connect biological principles with concrete engineering. It implies that establishing such a connection allows one to analyze and improve the environmental performance of engineered artifacts. Evidence presented in the previous chapters supports both parts of the second hypothesis.

Measures, metrics and indicators bridge the gap between bio-inspired guidelines based on biological principles and engineering applications of these guidelines. Chapter 3 first presents the guidelines and associated metrics for each. In Chapters 4-6, one sees how a few quantitative metrics connect abstract guidelines to concrete problems in engineering at multiple scales. Chapter 4 connects the micro/nano-structure guideline with contamination resistance and reduced cleaning burdens via contact angle. Using the simple metric of energy consumption rate per unit mass, Chapter 5 investigates two interpretations of a metabolic limit in the context of engineering. While the first, product centered interpretation proves less than reliable, the second highlights a potentially fundamental constraint on sustainable energy consumption rates. Chapter 6 uses ecosystem structure and flow regime metrics to concretize a guideline calling for ecological patterns in industrial resource flow networks. It first uses these metrics to compare ecosystems with industrial networks meant to mimic them, revealing that symbioses fall somewhere between linear production systems and ecosystems. Then, it uses the same metrics to design a carpet recycling network. In the process, one learns that network configurations desirable from a bio-inspired metric perspective also minimize life cycle environmental burdens and costs. Biological principles cast in the form of measures, metrics and indicators can influence engineering.

Each chapter that illustrates the use of metrics for translation and application also demonstrates the effectiveness of bio-inspired guidance at reducing or avoiding environmental burdens. Nature's self-cleaning surfaces exhibit high contact angles; Chapter 4's experiments imply a relationship between lower environmental burdens and high contact angle. The extended metabolism interpretation of the metabolic limit principle discussed in Chapter 5 leads one to the understanding that mass specific energy consumption rates correlate with environmental burdens and that a global sustainability limit may exist for this metric. As mentioned in the previous paragraph, desirable bio-inspired network configurations are also desirable from a traditional life cycle perspective. One finds holistic bio-inspiration environmentally relevant across multiple organizational and length scales.

7.2 Contributions

Exploring these hypotheses contributed new knowledge to the field of EBDM. This knowledge falls into one of three categories: discovery, development and confirmation / refutation. Discovery contributions generate new data or new interpretations of existing data. Development contributions refine or adapt existing methods or tools. Confirmation / refutation contributions test for previously identified outcomes and provide additional supporting or opposing data. The next three sections summarize this work's contributions in each of these three categories.

7.2.1 Discovery Contributions

As one might expect, the discovery of new knowledge began with biological principle extraction. Both the extraction process and its output led to discoveries. Turning first to the output, one sees that the metabolic limit principle's corresponding guideline is a unique contribution to EBDM. A constant comparative method assisted survey of EBDM literature found nothing comparable (See Chapter 3). This discovery via a new interpretation of biological data also proved new and intriguing to experts in the EBDM field (Gutowski 2008). The extraction process led to a pair of findings about the richness of EBDM and biology literature as sources for more guidelines and principles. Saturation is one reason to terminate coding. It refers to the point at which coding ceases to yield new categories or concepts that enrich existing categories. It is the author's opinion that saturation was achieved before exhausting the selected sample of EBDM literature. One could find the main themes in this comparatively young field during the course of one manual application of constant comparative method. Intriguingly, saturation did not occur with the biology literature. New and potentially applicable themes continued to emerge. Increasing the sample size limit for biological literature almost certainly would have added additional categories and enriching concepts.

The micro/nano structuring principle and the biological network patterns principle are known in the EBDM field; therefore, this dissertation cannot claim them as discovery contributions. However, investigations of the environmental efficacy of the guidelines derived from these principles led to two discoveries. First, experiments in Chapter 4 defined the magnitude of contamination resistance and self-cleaning one might expect from surfaces embodying the micro/nano structure guideline. This magnitude was not well defined in the open literature prior to this work. Second, in Chapter 6, comparisons between food webs and industrial symbioses quantified differences in the structures of these resource exchange networks. The structural differences highlight the gap between symbiosis achievement and intent.

7.2.2 Development Contributions

Adaptation of sociology's constant comparative method coding techniques for principle discovery stands as the dissertation's noteworthy development achievement. By successfully employing a modified version of CCM techniques, the dissertation demonstrates a new and novel approach to the generation of guidelines for EBDM. It also provides a more structured way to learn from nature. Importantly, this structured approach helps individuals with backgrounds outside the life sciences learn form nature when biologists or other life scientists are not available. One should note that combining the use of CCM and consultation with biologists enhances the value of the end result, as made evident by the biology review described in Chapter 3.

7.2.3 Confirmation / Refutation Contributions

In the course of scientific inquiry, some hypothesize and test while others test existing hypotheses. These later tests support or cast doubt upon initial findings and may lead to the confirmation or refutation of initial hypotheses. This work provides evidence supporting two concepts found in sustainable engineering while casting doubt upon a third.

Clearly, the results of this dissertation support the idea that bio-inspired guidelines can direct design at multiple scales toward environmentally preferable configurations. Since this type of guidance encorporates the influence of many environmental factors, it also demonstrates the effectiveness of taking a systems persepective when solving problems in EBDM. Multiple authors within and beyond the bounds of the EBDM community discuss biological guidance to support sustainable engineering (Benyus 1997, Beattie, et al. 2001, Korhonen, et al. 2005, Nielsen 2007). Evidence appearing in Chapter 3-6 lends credence to some of the claims advanced by these and other bio-inspired authors. The work with society scale SECR limits in Chapter 5 and resource networks in Chapter 6 illustrate the value of the systems perspective granted by using bio-inspired guidelines.

The belief that development from “Type I” through “Type II” to “Type III” industrial ecosystems results in environmental improvement in systems of production is one such bio-inspired concept (Graedel, et al. 1995). Industrial ecologists viewing this concept as vague and qualitative label it a “metaphor” while those finding concrete guidance consider it an analogy (Lifset 1997). Analyses in Chapter 6 reinforce arguments for the positive correlation between a transition from Type I to Type III industrial ecosystems and environmental improvements. Furthermore, the carpet network design problem’s results suggest that industrial ecologists can view ecosystem structures as analogs worthy of some degree of imitation in industrial systems.

In fact, observations recorded in Sections 6.2 and 6.3 cast doubt upon the value of the merely metaphorical view of bio-inspiration in industrial ecology. Current industrial symbioses structurally fall between linear production systems and food webs. Section 6.3 analyzes the outcome of a petro-chemical plant redesign performed by those viewing industrial ecology as the “waste equals food” metaphor. Quantitative analysis of their redesign revealed little improvement when compared with the original. In both analyses, merely metaphorical guidance falls short of the intended outcome.

7.3 Limitations

A number of limits and caveats became apparent during method development and bio-inspired guideline validation. The next four sections organize these limitations according to processes and principles with which they are associated. A fifth section discusses more philosophical limitations present in this work.

7.3.1 Constant Comparative Method and Principle Extraction Limitations

While successful at finding principles, important limits and weaknesses in CCM became apparent while modifying and applying it. CCM is:

- Tedious and time consuming (~4 months required to find and code ~100 articles, papers and book sections)
- Influenced by the initial literature sampling (bias, GIGO – garbage in equals garbage out)
- Influenced by the coder's ability to interpret encountered literature (i.e. If one is not familiar with microbiology or genetics, it is difficult to relate coded material from these areas to EBDM)
- Not helpful when prioritizing extracted principles

When applied to a sample taken from a far larger body of literature, two additional limitations of CCM based principle extraction appeared.

- A Complete set of living system principles was not found because the sample of biology literature did not "saturate" – more literature would have revealed more principles.
- Tacit assumptions in a field may prove difficult to detect

7.3.2 Micro/Nano Structure Guideline Limitations

Chapter 4 translates, applies and generates validating data for the micro/nano structure guideline. Taking a critical view of the chapter's experiment, one can criticize the representativeness of the part cleaned and the cleaning process.

- Simple feature geometry was tested. Intricate features or part geometry could change the observed results.
- Multiple methods for creating self-cleaning coatings exist. Only one type of coating was tested.
- Contaminants are legion, but only a few were tested.
- Other industrial cleaning processes (i.e. ultrasonic) exist and may interact differently with a self-cleaning surface.

7.3.3 Specific Energy Consumption Rate Limit Guideline Limitations

Chapter 5 translates, applies and generates validating data for the specific energy consumption rate limit guideline. Limitations related to this guideline include:

- Ambiguity with regard to the scale of design activity on which to apply it
- Uncertainty about its ability to predict sustainability limits caused by the paucity of established metrics with which its predictions can be compared

7.3.4 Bio-Inspired Network Guideline Limitations

Chapter 6 translates, applies and generates validating data for the biological network guideline. Limitations in the amount of available data are at the root of criticisms leveled against this guideline and its attendant conclusions.

- Only 29 proposed, existing or once operational industrial symbioses and integrated biosystems were available for analysis.
- Only one design problem was solved using this guideline and associated metrics.

7.3.5 On Guideline Quantification

The decision in Section 1.3.2 to use measures, metrics and indicators for bio-inspired environmental sustainability principles sets the dissertation on a quantitative footing. This quantitative foundation is a source of both strength and weakness. Quantification strengthens one's ability to use and test guidelines derived from living system principles. However, it also threatens to limit the breadth of application for identified principles.

Quantification gives a precise meaning for a bio-inspired environmental sustainability guideline. This precision allows one to formulate measureable goals and gage progress toward them. Such characteristics permit the use of guidelines in the many quantitative aspects of engineering design (i.e. optimization). They also increase the likelihood that those managing product portfolios and production facilities will track quantities relevant to the bio-inspired guidelines. If one cannot measure what he wishes to manage, how would he gage the result of interventions meant to improve the current situation? Clearly, he could not.

Despite the logic of the preceding paragraph, quantification can limit the extent to which one applies bio-inspired guidance. The same precision that makes measures, metrics and indicators attractive threatens to artificially constrain a potential user's perspective. In a narrow sense, it forces one of potentially many valid quantifications of a guideline on a user. The other quantifications may prove more applicable to a particular situation than the ones offered in this dissertation. Moreover, quantification engenders a belief that only one interpretation of a guideline is reasonable or even possible, introducing inflexibility. Such inflexible thinking is clearly undesirable when dealing with ideas that remain a topic of research and development in the realms of life science and design engineering.

In a broader sense, development of readily quantifiable biological principles into bio-inspired guidelines introduces an unintentional bias into this work. Other, less quantifiable, identified biological principles hold the potential to positively affect the environmental sustainability of engineering activities. Development of these other principles into actionable guidelines using non-quantitative representations was not pursued in this dissertation. A potential avenue for future work would involve qualitative statement of the insights inherent in difficult to quantify principles and development of a systematic process for extracting qualitative guidance.

7.4 Opportunities

Future opportunities for research and development at multiple scales of engineering interest manifest themselves during the course of this dissertation. Many of these aim to ameliorate limitations and criticisms stated in Section 7.3.

7.4.1 Refining Constant Comparative Method and Principle Extraction

Many of the CCM related limitations listed in Section 7.3 are caused by the large amount of qualitative data that a coder must manually search, assess and eventually code. Texts on CCM mention software meant to help practitioners take and organize code notes (Strauss, et al. 1998). Database mining tools (i.e. VantagePoint) extract, organize and quantify results from searches in online databases of academic literature. Combining tools of this kind holds the potential to reduce the time and tedium of the coding process while allowing an individual coder to process larger samples of life science literature.

Turning to the human side of the process, domain knowledge and familiarity with encountered scales influence the ability of a coder to extract concepts from the literature. The author's strengths in this regard tend toward larger scales (part to multi-facility) and center on physical sciences (i.e. thermodynamics, mechanics, etc.). Therefore, it may prove worthwhile to repeat the process with an engineer or engineer-microbiologist duo possessing greater comfort with smaller time, space and organizational scales. In this case, it would be appropriate to limit literature sampling to sources dealing with small scale biological phenomena.

7.4.2 Self-Cleaning Surface Technology Development and Standardization

Interesting opportunities for work with self-cleaning surfaces center on standards development and invention. Design of the experiment that forms the core of Chapter 4 necessitated a review of existing standards for surface cleanliness and cleaning. These standards do not account for the unique properties manifest by self-cleaning surfaces. Importantly, they do not define the level of post-soiling cleanliness or ease of cleaning needed to claim the self-cleaning surface label. As more companies make claims about the self-cleaning characteristics of products, it seems likely that a consensus definition will be needed to avoid false advertising. The need for such a definition and a test procedure to confirm it represents an opportunity to engage in the development of an ASTM, ISO or other standard for self-cleaning surfaces.

In an effort inspired by though not reported upon in this dissertation, micro-SLA was used to create micro-scale surface features with sizes and shapes similar to those found on lotus leaves. These experiments used hydroscopic resins. Application of hydrophobic coatings or use of hydrophobic resins would produce the desired surface chemistry. If made hydrophobic, surfaces with the observed type of geometry may enhance the hydrophobic effect to point where treated surfaces exhibit self-cleaning behavior. To the author's knowledge, micro-SLA has not been used to create a self-cleaning surface. Therefore, successful pursuit of this opportunity would lead to patentable technology.

7.4.3 Confirming the Metabolic Limit

A metabolic limit for human activity is one of the most intriguing and heretofore overlooked bio-inspired guidelines explored in this dissertation. Given its potential importance in the field of sustainable engineering and policy formulation for sustainable development, further confirmatory studies are in order. One such study extends the line of validation started in Chapter 5 by comparing extended metabolism values for individuals, nations and the globe to other environmentally focused sustainability measures, metrics and indices. Another interesting study would aim to generate an extended metabolic rate time series for individuals and nations passing through the industrial revolution. A third could investigate the impact of fueling an individual's extended metabolism using a large fraction of renewable energy sources. Would an escape from oxidation decouple extended metabolism and environmental impact?

7.4.4 Network Multiplication

Intriguing conclusions emerge from the network scale analysis and design problems in Chapter 6. However, they stand upon a limited data set. Further testing of these conclusions through modeling and design of other industrial resource distribution networks represents one related opportunity. Testing the conclusions in a dynamic network is a second opportunity. The biological metrics selected for the network study provide insight and guidance, but ecologists have developed other metrics for system level development (Ascendancy) and structure (modularity) that one may wish to investigate. Environmental conditions affect ecosystem structure. Exploring analogies between natural and business environments might aid in selecting the right types of ecosystem structures to use as models or starting points for resource network design.

7.4.5 The Next Ph.D.

Pursuit of the opportunities in the previous sections leads to projects of varying complexity and scope. Advisors and students may rightfully wonder which projects represent the best doctoral opportunities. This section briefly outlines four projects worthy of a doctorate in engineering or other science and technology related fields. The outlined projects focus on self-cleaning surfaces, metabolic thermodynamics, network design theory and the use of bio-inspiration, respectively.

An opportunity for innovation exists at the intersection of additive fabrication and self-cleaning surface technology. One summarizes the opportunity in the form of two research questions. Can additive fabrication technologies used for rapid prototyping or production create self-cleaning surfaces? If so, how might one create such surfaces using these technologies? As initially stated in the latter half of Section 7.4.2, micro-SLA work not documented in this dissertation took the first step toward answering these questions. However, generating micro-scale geometries in the size range found on Lotus leaves is only a first, though important, step. Creation of phobic surfaces, confirmation of contact angle enhancement and replication of micro-scale geometries over larger areas are other important milestones a researcher must achieve to succeed in this project. Successful completion of this work would mark the introduction of a new, novel and potentially patentable means of embodying the valuable self-cleaning working principle.

The observed correlation between extended metabolism and environmental impact deserves further investigation. One begins such an investigation by answering two confirmatory questions in the context of a master's project. Does the correlation hold for measures of environmental impact besides ecological footprint and allowable CO_2 emissions? Do other thresholds for environmental sustainability coincide with the observed 40 W/kg upper bound? If the answers prove positive, one may proceed with an analysis of the thermodynamic basis for these relationships, the doctoral opportunity present in this exploration. The objective of this second effort is to place these relationships on solid theoretical ground by identifying the common energetic and entropic connections between organism metabolism and each human's environmental impact.

Strong positive correlations between industrial resource distribution networks designed to minimize cost and emissions and those patterned after food webs suggest that a valuable source of untapped network design guidance exists in nature. Environmentally sustainable engineering stands to benefit from a research program meant to test, bound and eventually understand the physical basis for this guidance. As a first step, one should undertake a master's level program designed to test other resource distribution systems for the type of correlation observed in Chapter 6. If the correlation holds, one may proceed with a doctoral effort to understand the fundamental similarities between the two classes of networks. Understanding limits to the guidance imposed by fundamental differences is of equivalent importance. A theoretically correct and experimentally grounded method for bio-inspired resource distribution network design would serve as the ultimate goal of this work.

Leaving the realm of engineering, one may wish to examine the comparative effectiveness of learning from nature using different methods advanced in recent years. Multiple means of extracting information from the living world exist. The Biomimicry Institute developed a database of biological strategies matched with human challenges (AskNature.org), and it advocates direct collaboration with biology experts through its Biologist at the Design Table (BaDT) program. Advanced text searches of biology literature have been and are continuing to be developed to help engineers access biological knowledge (Chiu, et al. 2004, Mak, et al. 2004). Wilson proposed using Bond Graph models to represent biological phenomena during the engineering design process (Wilson 2008). This dissertation adapted CCM to serve a related purpose. Though not necessarily meant to provide the same type of design guidance, all of these methods attempt to aid those looking to the living world for answers to their design questions. Classification, organization and objective evaluation of these and other related methods might prove worthy of a design Ph.D. emphasizing the psychological processes occurring in a designer's mind (i.e. creativity, preference formation, fixation, etc.).

7.5 Validity and Meaning of Holistic Biomimicry

Holistic biomimicry is defined as the identification, translation and application of biologically inspired sustainability principles within the context of engineering. Methods for accomplishing these tasks appear in prior chapters, but holistic biomimicry is more perspective than method. I view this work as an effort to test this perspective's validity and grapple with its ultimate meaning in EBDM.

With this dissertation, I sought to evaluate whether or not a holistic view of living systems imparts environmentally beneficial guidance in engineering. I wished to learn whether laboring to achieve a holistic perspective brought greater insight or unnecessary complexity. It is with cautious optimism that I may report the former. Application of bio-inspired tenets generally leads to environmental improvement, and importantly, the suggested areas of improvement can prove surprising. For instance, a metabolic limit is not an outcome easily predicted using conventional EBDM thinking. It is an outcome that compactly encorporates the influence of many environmental factors, illustrating the systems perspective granted by using bio-inspired guidance. Such surprises represent some of the strongest proof that mankind has much to learn from the collection of organisms that tamed and maintained Earth's surface.

The middle, green way lies beyond awe though short of imitation. Some tend to marvel at the wonder of nature with the right eye while seeking a convenient dump site with the left. Others hope to substitute the human mind with the genetic sequence responsible for gecko feet. The course of this dissertation teaches that mankind can learn from life, but the lesson in its raw form requires interpretation. While environmentally sustainable products, processes and systems remain unchartered, monster-festoon regions on the map of design, holistic, bio-inspired guidelines offer a safer, systems-oriented alternative to plunging ahead with only retrospective techniques as a guide. However, I doubt that the course will always run true, as made evident by the case of the log-splitter in Chapter 5. Rather, we must remain open to interpreting the guidance, seeking inspiration from nature and refinement through engineering.

APPENDIX A

OPEN CODING MEMOS FOR BIOLOGY AND ECOLOGY

This appendix contains open coding memos used to generate the statements of biological principles found in Chapter 3. They represent a first filtering of the information found this dissertation's biological and ecological literature sample. Each memo focuses on identification of terms know in Constant Comparative Method (CCM) as concepts, properties and dimensions. Some also connect strings of concepts to form simple hypotheses and summary statements about the sampled qualitative data.

Coder	John Reap	Date	6/19/2007
Text Segment	Paragraphs: 1-5	Type	Memo
Reference	Axelrod, R. and W.D. Hamilton (1981) "The Evolution of Cooperation" *Science* 211: 1390-1396.		

"…evolutionary theory has recently acquired two kinds of extensions…genetical kinship theory and reciprocation theory."

Many of the major and encompassing ideas in biology appear in the first paragraphs. Concepts such as evolution, selection and fitness appear. New, more specific concepts such as genetic kinship and reciprocation theory occur for the first time. Group behavior is a concept related to kinship and reciprocity that bares the properties of cooperation, altruism and competition restraint which vary from low to high.

The ideas of mutualism and symbiosis are mentioned.

Potential Concepts: evolution, selection, fitness, genetic kinship, reciprocation theory, group behavior (P: cooperation D: low to high; P: altruism D: low to high; P: competition restraint D: low to high)

Text Segment	Paragraphs: 6-8	Type	Memo

"In the Prisoner's Dilemma game, two individuals can each either cooperate or defect. The payoff to the player is in terms of the effect on its fitness (survival and fecundity)."

Somewhat surprisingly, the authors turn to game theory to explain and model incidences of cooperation in the biological world. As the quoted passage indicates, they introduce the concept of the Prisoner's Dilemma, and they identify two properties for fitness, survival and fecundity. Both of these properties vary from low to high.

Potential Concepts: evolution, selection, fitness (P: survival D: low to high; P: fecundity D: low to high), genetic kinship, reciprocation theory, group behavior (P: cooperation D: low to high; P: altruism D: low to high; P: competition restraint D: low to high), Prisoner's Dilemma

Text Segment	Paragraphs: 16-31	**Type**	Memo

"…the evolution of cooperation can be conceptualized in terms of three separate questions…Robustness…Stability…Initial viability…"

In these paragraphs, it becomes apparent that cooperative behavior can stand alone as a concept. It has the dimensions: robustness, stability and initial viability. All of these can vary from low to high. The authors make noteworthy game theoretic arguments grounded in the Prisoner's Dilemma that support the robustness and stability of cooperation. I find their contention that kinship, a high degree of interaction and clustering of actors promotes the initiation of cooperative arrangements. In fact, I would go so far as to venture to guess that those three initiation approaches are ways of initializing cooperative behavior. Their mathematical arguments seem general enough to apply to situations in engineering without significant modification.

Potential Concepts: evolution, selection, fitness (P: survival D: low to high; P: fecundity D: low to high), genetic kinship, reciprocation theory, group behavior (P: cooperation D: low to high; P: altruism D: low to high; P: competition restraint D: low to high), Prisoner's Dilemma, cooperative behavior (P: robustness D: low to high; P: stability D: low to high; P: initial viability D: low to high, ways of achieving)

Table 68: Summary of potential concepts, properties and dimensions for Axelrod 1981

Concepts	Properties	Dimensions
Evolution	?	?
Selection	?	?
Fitness	Survival	Low to high
	Fecundity	Low to high
Genetic kinship theory	?	?
Reciprocation theory	?	?
Group behavior	Cooperation	Low to high
	Altruism	Low to high
	Competition restraint	Low to high
Cooperative behavior	Robustness	Low to high
	Stability	Low to high
	Initial Viability	Low to high
		Way of achieving (kinship, high interaction frequency, clustering)

Coder	John Reap	Date	7/19/2007
Text Segment	Paragraphs: abstract-?	Type	Memo
Reference	Azaele, S., S. Pigolotti, J.R. Banavar and A. Maritan (2006) "Dynamical evolution of ecosystems." *Nature* 444: 926-928.		

"Here we consider the dynamical behaviour of a community, and benchmark it against the exact predictions of a neutral model near or at stationarity."

Community is the main concept in this short, terse, statistically oriented paper. It is given properties of size, dynamics, and persistence. Complicated empirical statistical relations quantify some of these dimensions. Relative species abundance is a dimension for size; species turnover distribution is a dimension for dynamics. While the reasoning is opaque to me, these equations allow the authors to estimate the length of time an ecosystem is expected to exist or, at least, needs to recover from perturbation.

Overall this was not a terribly useful article.

Potential Concepts: community (P: size D: relative species abundance; P: dynamics D: species turnover distribution; P: persistence D: ?)

Table 69: Summary of potential concepts, properties and dimensions Azaele 2006

Concepts	Properties	Dimensions
Community	Size	Relative species abundance
	Dynamics	Species turnover distribution
	Persistence	?

Coder	John Reap	Date	6/7/2007
Text Segment	Paragraphs: entire article	Type	Memo
Reference	Baldauf, S.L. (2003) "The Deep Roots of Eukaryotes" *Science* 300: 1703-1706.		

"Molecular phylogenetic trees have gradually assigned most of the cultivated and characterized eukaryotes to one of eight major groups."

In Baldauf's short article, classification is the dominant concept. He describes the microbiological community's struggles with classifying the tree of life's various members. He focuses on eukaryotes, but the discussion reveals two properties (or strategies for) of biological classification, namely genetic and feature based. The genetic markers are not clear to me, but features include the presence or absence of nuclei, mitochondria, chloroplasts, rigid cell walls and other distinct cell elements. At one point he mentions differences between the mitochondria in opisthokonts and other eukaryotes; so, a feature's particular configuration also serves as a dimension for the feature based property.

Potential Concepts: classification (P: genetic; P: feature based D: presence or absence, configuration)

Table 70: Summary of potential concepts, properties and dimensions for Baldauf 2003

Concepts	Properties	Dimensions
Classification	Genetic	?
	Feature based	Presence or absence
		Configuration

Coder	John Reap	Date	7/30/2007
Text Segment	Paragraphs: abstract - 6	Type	Memo
Reference	Bascompte, J., P. Jordano, and J.M. Olesen (2006) "Asymmetric Coevolutionary Networks Facilitate Biodiversity Maintenance." *Science* 312: 431-433.		

"Each network displays information on the mutual dependence or strength between each plant and animal species, mainly measured as the relative frequency of visits."

Organism interactions and interaction networks dominate this article. Biodiversity appears as a related concept. Organism interactions have properties of strength and symmetry. Strength is measured in terms of visits. This dimension seems largely to be a consequence of the authors' interest in mutualistic interactions; it seems reasonable that antagonistic interactions would be measured as flows of energy and material (i.e. prey consumption). Asymmetry varies according to an index of asymmetry. Asymmetry measures the difference in dependence between two members of an interacting pair. A high degree of asymmetry corresponds with a situation in which one member is far more dependent upon the other while high symmetry indicates approximately equal dependence.

Potential Concepts: organism interactions (P: strength D: visits; P: symmetry D: index of asymmetry), interaction network, biodiversity

Text Segment	Paragraphs: 8-end	**Type**	Memo

"A more meaningful measure of network complexity is provided by the concept of species strength."

We see that interaction networks have properties such as type, complexity and heterogeneity as the article progresses. Type varies discretely as mutualist. Complexity varies dimensionally by species strength (sum of interactions for a species in a network) and species degree (number of interactions per species – average?). Heterogeneity seems related to asymmetry, but its dimensions are not clear. According to the authors, a heterogeneous interaction network is characterized by many species with few interactions and a few species with many interactions.

The authors find that mutualistic interaction networks are composed of a few strong species, highly asymmetric organism interactions and significant heterogeneity.

Potential Concepts: organism interactions (P: strength D: visits; P: symmetry D: index of asymmetry), interaction network (P: type D: mutualist; P: complexity D: species strength, species degree; P: heterogeneity D:?), biodiversity

Table 71: Summary of potential concepts, properties and dimensions for Bascompte 2006

Concepts	Properties	Dimensions
Organism interactions	Strength	Visits
	Symmetry	Index of asymmetry
Interaction network	Type	Mutualist
	Complexity	Species strength
		Species degree
	Heterogeneity	?
Biodiversity	?	?

Coder	John Reap	Date	6/6/2007
Text Segment	Paragraphs: abstract to end	Type	Memo
Reference	Baum, C., W. Meyer, R. Stelzer, L.-G. Fleischer and D. Siebers (2001) "Average nanorough skin surface of the pilot whale (Globicephala melas, Delphinidae): considerations on the self-cleaning abilities based on nanoroughness" *Marine Biology* 140: 653-657.		

This article about pilot whale skin discusses marine soiling as much as the features and behaviors pilot whales employ to defeat it. The abstract introduces concepts such as biofouling, microfouling and microniches in an effort to explain the soiling conditions confronted by aquatic organisms. Biofouling seems to have the property of initiating conditions which varies dimensionally by type. In this paper, the authors mention carbon residue deposition as a type of initiating condition. It would seem reasonable that biofouling might have other properties such as development rate and extent, but since these are not mentioned, they will not be added to Table 72. Microniches, the skin surface habitats that biofouling microorganisms can inhabit, have properties of size and occurrence which respectively vary by micrometers and many to few.

The authors do mention the concept of self-cleaning. As employed, self-cleaning possesses the properties of passive and active which both vary dimensionally by type. Passive self-cleaning is accomplished by the formation of nanoridges on the skin of pilot whales. The authors argue that these nanoridges create enclosures that are too small for many microorganisms, forcing them to inhabit tips of ridges exposed to higher hydrodynamic forces. Active self-cleaning depends upon two mechanisms. The first, "epidermal desquamation," is essentially microscale shedding of skin particles. The second is a behavior that enhances passive self-cleaning. When marine mammals possessing nanorough skin features leap from the water, they expose microorganisms and soiling particles to smaller boundary layers and air-water interfaces which result in increased hydrodynamic forces.

Potential Concepts: biofouling (P: initiating condition D: type), microfouling, microniches (P: size D: micrometers; P: occurrence D: few to many), self-cleaning (P: passive D: type; P: active D: type)

Table 72: Summary of potential concepts, properties and dimensions for Baum 2001

Concepts	Properties	Dimensions
Biofouling	Initiating condition	Type (i.e. carbon residue deposition)
Microfouling	?	?
Microniches	Size	Micrometers
	Occurrence	Many to few
Self-Cleaning	Passive	Type (i.e. nanorough surfaces)
	Active	Type (i.e. epidermal desquamation, air-water transition induced boundary layer reduction)

Coder	John Reap	Date	7/23/2007
Text Segment	Paragraphs: all	Type	Memo
Reference	Becks, L., F.M Hilker, H. Malchow, K. Jurgens and H. Arndt (2005) "Experimental demonstration of chaos in microbial food web." *Nature* 435: 1226-1229.		

"…system includes chaotic behaviour, as well as stable limit cycles and coexistence at equilibrium."

Chaotic behavior and food webs are the main concepts present in this article. Chaotic behavior has properties of type and degree. The types of chaotic behavior include chaotic, limit cycles and equilibrium; a difference between true chaos and deterministic chaos is also present. Degree is measured using Lyapunov exponents. Positive Lyapunov exponents indicate chaotic behavior while negative exponents indicate the opposite. This test seems straightforward and may prove useful if chaotic behavior becomes an important part of my work.

A microbe population serves as the authors' experimental apparatus, and population levels are data points. Fluctuations in these population levels, population dynamics, constitute the research substance of the article. Population dynamics are driven by forcing factors which vary dimensionally and discretely between extrinsic and intrinsic.

Potential Concepts: chaotic behavior (P: Type D: chaotic to equilibrium, true to deterministic chaos; P: degree D: Lyapunov exponents), food webs, population dynamics (P: forcing factors D: extrinsic or intrinsic)

Table 73: Summary of potential concepts, properties and dimensions for Becks 2005

Concepts	Properties	Dimensions
Chaotic behavior	Type	Chaotic, limit cycle, equilibrium
		True to deterministic
	Degree	Lyapunov exponents
Food webs	?	?
Population dynamics	Forcing factors	Extrinsic
		Intrinsic

Coder	John Reap	Date	7/23/2007
Text Segment	Paragraphs: all	Type	Memo
Reference	Bell, T., J.A. Newman, B.W. Silverman, S.L. Turner and A.K. Lilley (2005) "The contribution of species richness and composition to bacterial services." *Nature* 436: 1157-1160.		

"Biodiversity influences the way in which ecosystems function...there is a decelerating relationship between community respiration and increasing bacterial diversity."

This article reinforces previously identified concepts such as biodiversity and ecosystem. Once again, one find magnitude to be biodiversity's defining property; it varies by species richness and species composition. Richness is a simply the number of species while composition seems to have something to do with the functional roles taken by different species. The paper discusses ecosystems from the perspective of function which varies dimensionally by type (i.e. productivity).

The complement mechanism and the selection mechanism are invoked as the two possible explanations for biodiversity's influence on ecosystem functions. Increasing magnitudes of biodiversity are found to enhance the productivity function of ecosystems. They find evidence that richness (complement mechanism) and composition (selection mechanism) cause this behavior, but they believe the majority of the influence stems from simple species richness. While the influence of richness saturates, they observe that productivity was still increasing at 72 bacteria species, the maximum number of microbes used in their experiments.

Potential Concepts: biodiversity (P: magnitude D: species richness, species composition), saturation, ecosystem (P: function D: type)

Table 74: Summary of potential concepts, properties and dimensions for Bell 2005

Concepts	Properties	Dimensions
Biodiversity	Magnitude	Species richness
		Species composition
Saturation	?	?
Ecosystem	Function	Type (i.e. productivity)

Coder	John Reap	**Date**	7/5/2007
Text Segment	Paragraphs: abstract - 6	**Type**	Memo
Reference	Belyea, L.R. and J. Lancaster (1999) "Assembly rules within a contingent ecology" *Oikos* **86**: 402-416.		

"…we review the literature on community assembly within the context of three principal determinants: dispersal constraints, environmental constraints and internal dynamics."

Belyea's and Lancaster's paper represents an attempt to summarize previously identified community assembly rules and reconcile their influence with that of environmental constraints.

Scale is a defining property for the assembly rule concept. Apparently, some rules apply within particular scales while others span multiple scales. Scale varies dimensionally by distance and organizational level. Environmental constraints have the properties of type, effect and frequency. The authors give examples of different types of environmental constraints, but they are not forthcoming with different classes. The effect property varies from slight to dominant while frequency varies from chaotic through periodic to constant.

Potential Concepts: assembly rule (P: scale D: distance, organizational level), environmental constraints (P: type D:?; P: effect D: slight to dominant; P: frequency D: chaotic through periodic to constant)

Text Segment	p. 405	**Type**	Memo

Of course, the rules listed by this paper's coauthors are of interest. Rules 1, 2 and 8 are of particular interest and are worth restating in this memo.

1. Resource utilization within guilds tends to increase due to interspecific competition

2. Resource utilization across guilds or functional groups tends to increase due to interspecific competition

8. A greater proportion of available energy and nutrients is retained in the biomass, due to selection of species which cycle energy and nutrients more efficiently

These three rules would seem to have bearing on the study of industrial eco-parks and larger scale industrial ecologies.

Text Segment	Paragraphs: 8-end	**Type**	Memo

Most of the remainder of this paper discusses the rules listed on page 405 and the influence of environmental constraints upon them. Ideas such as overdispersed, underdispersed, <u>niche overlap</u>, <u>R* rule</u>, <u>P* rule</u> are discussed in relation to the list of assembly rules. It might be worth revisiting this paper as assembly rule concepts from other works surface.

Potential Concepts: assembly rule (P: scale D: distance, organizational level), environmental constraints (P: type D:?; P: effect D: slight to dominant; P: frequency D: chaotic through periodic to constant), niche overlap, R* rule, P* rule

Table 75: Summary of potential concepts, properties and dimensions for Belyea 1999

Concepts	Properties	Dimensions
Assembly rules	Scale	Distance
		Organizational level
Environmental constraints	Type	?
	Effect	Slight to dominant
	Frequency	Chaotic through periodic to constant
Niche overlap?		
R* rule?		
P* rule?		

Coder	John Reap	Date	7/11/2007
Text Segment	Paragraphs: all	Type	Memo
Reference	Berryman, A.A. (2003) "On principles, laws and theory in population ecology" *Oikos* 103 (3): 695-701.		

"…many organisms alter physical structure and change chemical reactivity in ways that are independent of their assimilatory or dissimilatory influence."

This article states five major ecological concepts encountered in previous coding exercises. The include: Malthusian law (exponential growth of populations), Allee effect (population growth enhancement arising from cooperation), competition, interaction and Liebig's Law (limiting factors). The author considers these five concepts to be principles of population ecology. This article serves to strength then codes present in other articles and identified in earlier memos. It primarily adds different quantifications of these concepts and is worth consulting again should population dynamics contribute a principle to the list of sustainable engineering principles.

Potential Concepts: Malthusian law, Allee effect, competition, interaction, Liebig's Law

Table 76: Summary of potential concepts, properties and dimensions for Berryman 2003

Concepts	Properties	Dimensions
Malthusian	?	?
Allee effect	?	?
Competition	?	?
Interaction	?	?
Liebig's Law	?	?

Coder	John Reap	Date	3/8/2007
Text Segment	Paragraphs: abstract to p. 394	Type	Memo
Reference	Blanckenhorn, Wolf U. (2000) "The Evolution of Body Size: What Keeps Organisms Small?" *The Quarterly Review of Biology* 75 (4): 385-407.		

Extracting general concepts from this article is proving difficult. <u>Selection</u> is a recurring theme with the property of <u>type</u> which varies dimensionally between either <u>sexual</u> or <u>viability</u>. Since the article focuses on viability selection's role in determining organism body size, it contains a lengthy discussion about proposed types of viability selection and evidence supporting each. Viability and body size could be concepts. But, these concepts are not general; they do not extend beyond the realm of biology.

Potential Concepts: selection (P: type D: sexual, viability)

Text Segment	Paragraphs: p. 398-399	Type	Memo

"Cope's rules state that: (1) taxa evolve to larger body size over evolutionary time, and (2) that larger organisms and taxa are more likely to go extinct."

In the closing pages of this work, I find some general statements about size and its inherent risks. But, what is general enough to extend beyond the realm of biology; can any of this be applied to something besides organisms? Returning to the idea of using <u>viability</u> as a concept, I could assign it the properties of <u>energetic</u>, <u>agility</u> and <u>temporal</u>. The energetic property might have dimensions of <u>required growth energy</u>, <u>maintenance</u>

energy and heat dissipation. The dimension for temporal viability might be development time. But, the dimension for agility is not clear.

Potential Concepts: viability (P: energetic D: required growth energy, D: maintenance, D: heat dissipation; P: temporal D: development time; P: Agility)

Table 77: Summary of potential concepts, properties and dimensions for Blanckenhorn 2000

Concepts	Properties	Dimensions
Viability	Energetic	Required growth energy, maintenance energy, heat dissipation
	Temporal	Development time
	Agility	?
Selection	Type	Sexual, viability

Coder	John Reap	**Date**	6/11/2007
Text Segment	Paragraphs: abstract to para. 2	**Type**	Memo
Reference	Briand, Frederic. (1983) "Environmental Control of Food Web Structure" *Ecological Society of America* **64** (2): 253-263.		

"The past decade has seen a surge of interest in food web structure and organization..."

The concept of a food web appears early in this paper. It possesses properties such as size which is dimensioned by species richness and structure which is dimensioned by connectance and interaction strength.

Potential Concepts: food web (P: size D: species richness; P: structure D: connectance, interaction strength)

Text Segment	Paragraphs: para. 3-end	Type	Memo

"…two broad categories of ecosystems: those exposed to high and those exposed to low temporal variability of the physical environment."

The author's concept of the physical environment encompasses both resources and harshness. He mentions resources such as water, and he mentions factors such as pH and salinity which could dictate harshness. Factors such as temperature could be counted as either. The author focuses on temporal variability of the physical environment, which gives rise to the properties of temporal resource variability and temporal harshness variability. It is reasonable to state that both vary from low to high.

This author connects variability and food web structure; specifically, he shows that connectance declines as the temporal variability of the physical environment increases. He suggests that organisms rely on a few intense feedings when environments are highly variable and that they utilize a diverse set of resources to a far lesser degree in stable environments. I should watch for support or refutation of these findings in other work related to food webs and connectance.

Potential Concepts: food web (P: size D: species richness; P: structure D: connectance, interaction strength), physical environment (P: temporal resource variability, D: low to high; P: temporal harshness variability D: low to high)

Table 78: Summary of potential concepts, properties and dimensions for Briand 1983

Concepts	Properties	Dimensions
Food web	Size	Species richness
	Structure	Connectance
Physical environment	Temporal resource variability	Low to high
	Temporal harshness variability	Low to high

Coder	John Reap	Date	1/26/2007
Text Segment	Paragraphs: abstract - 13	Type	Memo
Reference	Brown, J., and G. West (2004) "One rate to rule them all" *New Scientist* **182**: 38-41		

"…ecology has little in the way of universal laws or principles…investigating forces behind a host of ecological patterns…identified one factor [having] dramatic ecological consequences: metabolic rates…"

Three concepts emerge in the abstract: <u>absence of laws</u>, <u>ecological patterns</u> and <u>metabolic rates</u>. The absence of laws akin to those found in other sciences such as physics motivates the authors. In most other sciences, a lack of laws would tragically hinder development of theory; an absence of laws would indicate a primitive state of theoretical development in said science. What types of inquiry would this hinder? Certainly, experimental work could occur. Would the lack of ecological theory hamper or prevent multidisciplinary work; without general guidance, would comparisons between particular instances prove useless?

Of course, ecological patterns and an absence of laws are related. Without the latter, one cannot predict or entirely explain the former. This relationship is obvious and clearly revealed when the authors bemoan the fact that knowing "ecological rules" in one locale does not provide much insight into those in another. This is the point where metabolic rate enters the picture. A metabolic rate law capable of explaining some ecological patterns may exist, or perhaps, one should think of observed metabolic trends as an ecological pattern – making metabolic rate a property of ecological patterns. Either way, the authors clearly believe in the predictive capacities of metabolic rates. They cite cases in which metabolic rates predict organism life spans and the distances between trees in forests.

Potential Concepts: absence of laws, ecological patterns (P: metabolic rate? D: ??)

Text Segment	Paragraphs: 14-21	Type	Memo

"…the pace of life accelerates about threefold for every 10 C increase in temperature…"

Noting that ecological diversity tends to increase in warmer climates, the authors begin to discuss the relationship between temperature and metabolic rate. They introduce the concept of <u>pace of life</u>. They attribute properties such as metabolic rate, <u>ecological interactions</u>, <u>speciation</u> and <u>extinction</u> to the pace of life concept. All of these terms lend themselves to dimensional classifications such as <u>high to low</u>.

Potential Concepts: pace of life (P: metabolic rate D: high to low; P: ecological interactions D: many to few; P: speciation D: high to low; P: extinction D: high to low)

Text Segment	Paragraphs: 22-24	Type	Memo

"…fossil fuel use can be thought of as part of the 'metabolism' of our species…"

Here, the authors attempt to exercise the predictive capacity of their metabolic relationships in a domain beyond that usually associated with ecology. They consider the consequences of counting humanity's use of fossil fuels and other energy resources as part of its metabolism. Counting annual per capita energy consumption as a form of metabolism, they calculate the effective mass of women in wealthy countries, and then, they use effective mass to estimate fertility values less than 2 children per mother – approximately correct for the industrialized world. They effectively introduce a concept that one might call <u>extended metabolism</u>.

Potential Concepts: extended metabolism

Table 79: Summary of potential concepts, properties and dimensions for Brown 2004

Concepts	Properties	Dimensions
Pace of life	Metabolic rate	High to low
	Ecological interactions	Many to few
	Speciation	High to low
	Extinction	High to low
Ecological patterns	Metabolic rate?	?
Absence of laws	?	?
Extended metabolism	?	?

Coder	John Reap	Date	3/8/2007
Text Segment	Paragraphs: abstract to 2	Type	Memo
Reference	Bunn, Stuart E. and Angela H. Arthington (2002) "Basic Principles and Ecological Consequences of Altered Flow Regimes for Aquatic Biodiversity." *Environmental Management* 30 (4): 492-507.		

"…flow is a major determinant of...biotic composition…[and]…patterns of longitudinal and lateral connectivity is essential to the viability of populations…"

From the start, I see a focus on connections. It is the strength and type of connection that determines the "…sustainability of rivers and their associated floodplain wetlands." A cleanly defined concept is not yet apparent, but it seems likely that said concept will having something to do with connections, connectivity or the like.

Text Segment	Paragraphs: 3-18	Type	Memo

Though influenced by the context of its extraction, <u>flow</u> emerges as a convenient way in which to contemplate connections. The authors repeatedly make the point that flow influences multiple river ecosystems on multiple scales which suggests the generality of the concept. Flow possesses identifiable properties such as <u>magnitude</u> and <u>variability</u>. Magnitude varies dimensionally from <u>no flow</u> to <u>peek</u>; variability seems to possess dimensions of <u>random</u>, <u>periodic</u> and <u>constant</u>.

This is the third article that combines ideas about nodes, connections, networks and sustainability of individuals, populations or ecosystems. This may represent the emergence of some kind of principle for environmentally sustainable networks, but it is too early to know. The flow presented in this article differs with that in others in that organisms live in the flow. This flow is not between organisms or groups of organisms. I expect that some of the terms used in the memos for these related articles will be similar and that it will be possible to consolidate them.

Potential Concepts: flow (P: magnitude D: no flow to peek; P: variability D: random, periodic and constant)

Text Segment	Paragraphs: 19-24	Type	Memo

"Many species in streams with highly variable flow regimes have evolved life history strategies that ensure strong recruitment despite disturbances…"

A new concept appears in this section. The idea of <u>flow adaptation</u> takes center stage. The authors discuss flow adaptation in the context of fish reproduction. While making the influence of flow clear, this context also makes it difficult to abstract properties and dimensions for flow adaptation.

Potential Concepts: flow adaptation

Text Segment	Paragraphs: 25-end	Type	Memo

"…viability of populations…depends on their ability to move freely through the stream network."

In these paragraphs, connectivity takes the fore. The authors recount many examples of ecosystem change and population declines resulting from the loss of stream integrity caused by the placement of dams and other structures. It is, however, hard to find "nodes" that are connected. Fish and other organisms simply take advantage of the existence of the stream. The main point seems to be that a decline in stream continuity leads to changes; so, perhaps, the concept under discussion is continuity. One might cast continuity as a property of flow instead of an independent concept. Recasting as a property, continuity would seem to vary dimensionally between continuous to discontinuous.

Potential Concepts: (P: continuity D: continuous to discountinuous)

Table 80: Summary of potential concepts, properties and dimensions for Bunn 2002

Concepts	Properties	Dimensions
Flow	Magnitude	No flow to peek
	Variability	Random, periodic and constant
	Continuity	Continuous to discontinuous
Flow adaptation	?	?

Coder	John Reap	Date	6/15/2007
Text Segment	Paragraphs: 5 to ?	Type	Memo
Reference	Cadenasso, M.L., S.T.A Pickett and K.C. Weathers. "Effect of Landscape Boundaries on the Flux of Nutrients, Detritus, and Organisms" in *Food Webs at the Landscape Level*. (2004) G.A. Polis, M.E. Power and G.R.Huxel Eds. University of Chicago Press: London.		

"…boundaries may influence the trophic structure and dynamics of food webs."

Food webs provide context for this article, but they do not figure prominently from a coding perspective. Once again, one sees properties for food webs such as structure and dynamics. But, the boundary concept is the focus of this article. The authors discuss the influence boundaries can have on food web properties. One quickly learns that boundary properties include structure and function. As one proceeds, composition joins the list of properties for boundaries. Function varies dimensionally by type (i.e. nutrient flux control, detritus flux control and organism flux control). Composition varies by number of species. Dimensions for boundary structure are not immediately clear.

Considering boundary architecture synonymous with boundary structure, one learns that the dimensions of boundary structure are the amount and morphology of a boundary's constituent elements. In the case of forests, the authors find that boundary structure influences boundary function. It is likely that it influences the structure and dynamics of food webs as well.

Potential Concepts: food web (P: structure D: ?; P: Dynamics D: ?), boundary (P: structure D: amount of constituent elements, morphology of constituent elements; P: function D: type; P: composition D: number of species)

Table 81: Summary of potential concepts, properties and dimensions for Cadenasso 2004

Concepts	Properties	Dimensions
Food web	Dynamics	?
	Structure	?
Boundary	Structure	Amount of constituent elements (i.e. measured in biomass for a forest)
		Morphology of constituent elements
	Function	Type (i.e. nutrient flux control, detritus flux control and organism flux control)
	Composition	Number of species

Coder	John Reap	Date	7/19/2007
Text Segment	Paragraphs: abstract-end	Type	Memo
Reference	Cardinale, B.J., D.S. Srivastava, J.E. Duffy, J.P. Wright, A.L. Downing, M. Sankaran and C. Jouseau. (2006) "Effects of biodiversity on the functioning of trophic groups and ecosystems." *Nature* 443: 989-992.		

"…average species loss does indeed affect the functioning of a wide variety of organisms and ecosystems, but the magnitude of these effects is ultimately determined by the identity of species that are going extinct."

Biodivesity, ecosystem and trophic group are the major concepts in this article. Biodiversity's property of magnitude which varies dimensionally by number of species serves as the independent variable in the authors' meta-analysis of biodiversity studies. Many other studies relate biodiversity's affects to ecosystems or food webs, but this one focuses on properties of trophic groups such as biomass stock and resource depletion. They introduce relative dimensions for each of these properties. Mean log ratio and peak log ratio respectively compare average and maximum performing monocultures with polycultures of varying diversity.

The authors find that high magnitudes of biodiversity correlate with high mean log ratios for both biomass stock and resource depletion. However, peak log ratios for those two trophic group properties are approximately zero, indicating no difference between biodiverse plots and the best performing monocultures.

Potential Concepts: biodiversity (P: magnitude D: species richness), ecosystem, trophic group (P: biomass stock D: mean log ratio, peak log ratio; P: resource depletion D: mean log ratio, peak log ratio)

Table 82: Summary of potential concepts, properties and dimensions for Cardinale 2006

Concepts	Properties	Dimensions
Trophic group	Biomass stock	Mean log ratio
		Peak log ratio
	Resource depletion	Mean log ratio
		Peak log ratio
Biodiversity	Magnitude	Number of species
Ecosystem	?	?

Coder	John Reap	Date	4/11/2007
Text Segment	Paragraphs: abstract to end	Type	Memo
Reference	Chapman, Michael J. and Lynn Margulis (1998) "Morphogenesis by symbiogenesis." *International Microbiology* 1: 319-326.		

"Symbiosis is simply organisms of different species living in close contact…Symbiogenesis…refers to…new physiologies…as a direct consequence of symbiosis."

This paper's primary concepts appear in the abstract and introduction. The authors choose to discuss concepts such as morphogenesis, cyclical symbiont integration, symbiogenesis, and symbiosis. Of these, it seems that only symbiosis is strongly developed in this paper. One learns that the properties of symbiosis include partner specificity, information transfer extent, association period and partnership range. Partner specificity varies dimensionally from one to many species. Information transfer varies from chemical signals to gene transfer. Association period varies between temporary and permanent, but this dimensional variation is not as strongly supported as the others. Partnership range seems to vary from parasitism to co-dependence.

Unfortunately, development of the other identified concepts is not nearly as extensive. I may need to code other articles about symbiosis before some of the other details in this article become apparent.

Potential Concepts: morphogenesis, cyclical symbiont integration, symbiogenesis, and symbiosis (P: partner specificity D: one to many species; P: information transfer extent D: chemical signal to gene transfer; P: association period D: temporary to permanent; P: partnership range D: parasitism to co-dependence

Table 83: Summary of potential concepts, properties and dimensions for Chapman 1998

Concepts	Properties	Dimensions
Symbiosis	Partner specificity	One to many species
	Information transfer extent	Chemical signal to gene transfer
	Association period	Temporary to permanent
	Partnership range	Parasitism to co-dependence
Morphogenesis	?	?
Cyclical symbiont	?	?
Symbiogenesis	?	?

Coder	John Reap	Date	6/19/2007
Text Segment	Paragraphs: abastract-2, 7-8	Type	Memo
Reference	Chase, Jonathan M. (2000) "Are there real differences among aquatic and terrestrial food webs?" *Trends in Ecology and Evolution* 15 (10): 408-412.		

"A trophic cascade is defined as a strong effect imposed by top predators…[that] plays an important role in determining the overall structure of the community."

The trophic cascade concept is central to this paper. The author questions statements and work by others that suggest an increased prevalence of cascades in aquatic ecosystems. Trophic cascades may be synonymous with the idea of top-down effects, though use of both words in the author's abstract suggests the contrary. Length might be a property of trophic cascades. While some trophic cascades extend to producers, others only seem to affect a few links in a food chain.

Ecosystems and food webs are other important concepts in this paper. This paper mentions the food web properties of structure and complexity. Complexity varies dimensionally from high to low. Interestingly, more complex food webs may be less influenced by trophic cascades. The author observes that simple ecosystems such as artic tundra show more evidence for trophic cascades than lakes.

Potential Concepts: trophic cascade (P: length D:?), ecosystem, food web (P: structure D:?; P: complexity D: low to high)

Table 84: Summary of potential concepts, properties and dimensions for Chase 2000

Concepts	Properties	Dimensions
Trophic cascade	Length	?
Ecosystem	?	?
Food web	Structure	?
	Complexity	Low to high

Coder	John Reap	Date	7/11/2007
Text Segment	Paragraphs: 17-end	Type	Memo
Reference	Colyvan, Mark (2003) "Laws of nature and laws of ecology" *Oikos* 101(3): 649-653.		

"…Kleiber allometry: basal metabolism rate is proportional to a ¾ power of body weight."

Colyvan devotes most of his article to describing what the laws of nature are not. He cites some references which may be of use later, but most of his discussion is not related to biology or ecology per se.

Toward the end, he introduces two laws which I will label as concepts – Kleiber allometry and Malthusian growth. Kleiber allometry has appeared in other articles and papers as the metabolic scaling law. Murrays statement simply reinforces its importance without adding any new properties. Malthusian growth applies to the study of population dynamics, and it seems to share the property of inertia with Newton's first law. I have heard about population "inertia" in the past, but I do not know how it would vary dimensionally.

Potential Concepts: Kleiber allometry, Malthusian growth (P: inertia D:?)

Table 85: Summary of potential concepts, properties and dimensions for Colyvan 2003

Concepts	Properties	Dimensions
Kleiber allometry	?	?
Malthusian growth	Inertia	?

Coder	John Reap	Date	6/26/2007
Text Segment	Paragraphs: 1-10	Type	Memo
Reference	Cousins, S.H. "Food Webs: From the Lindeman Paradigm to a Taxonomic General Theory of Ecology" in *Food Webs Integration of Patterns & Dynamics*. (1996) G.A. Polis and K.O. Winemiller Eds. Chapman & Hall: New York.		

"The concept of ecosystem is of particular importance to a general theory of ecology and it is shown how the ecosystem can be defined from the food web."

Ecosystem, food chain, and food web are common ecological concepts that appear in the first few paragraphs. Food chains seem to have the property of length which varies dimensionally by number of trophic levels. However, this author finds fault with using trophic categories to define food webs. He finds that food webs have two defining properties: categories and trophic relations, which he further generalizes to stocks and flows.

Potential Concepts: food chain (P: length D: number of trophic levels), food web (P: categories or stock D: ?; P: trophic relations D: ?)

Text Segment	Paragraphs: 11-end	Type	Memo

"…new scaling arises when we consider biological processes as concentrators which create local organizations, or concentration, by capturing solar-derived energy...."

Here, the author begins to rely upon thermodynamic arguments to support his position that body mass and taxonomic groups should define the stocks in a food web. He introduces the ecology concept of a sink web, which seems to be the list of all organisms and feeding flows required to support said organism. He also uses the term available energy, which has the property of amount that varies dimensionally by body size. Now, this is a curious way to measure available energy. On one hand, a larger body would have more energy, but on the other, he seems to mix Second Law ideas into his discussion that, for me, confuse his meaning.

The self-organizing system concept implicit in the quoted passage appears later in this article with the property system attractor. In this article, system attractors vary dimensionally by type; the author mentions top predators such as lions. The author contends that system attractors in self-organizing systems determine the direction of energy flow in an area. He labels the combination of a self-organizing system and its geographical extent an ecosystem trophic module. An equivalent and more descriptive name for this concept is photon shed. Regardless of the name, it is clear that ecosystem trophic modules possess the property of extent that varies dimensionally by area and potentially volume.

In the end, the author reiterates his belief that "…body size is the key description of energy availability in food webs and is thus a thermodynamic description." This is a noteworthy statement if one combines it with past findings regarding the potential universality of specific metabolic rates. If a system's components have a maximum allowable energy throughput, is it not reasonable to believe that a system of such components reflects this constraint in some discernable way?

Potential Concepts: food chain (P: length D: number of trophic levels), food web (P: categories or stock D: ?; P: trophic relations D: ?), sink web, available energy (P: amount D: body size), self-organizing system (P: system attractor D: type), ecosystem trophic module (P: extent D: area, volume)

Table 86: Summary of potential concepts, properties and dimensions for Cousins 1996

Concepts	Properties	Dimensions
Food web	Categories or stocks	?
	Trophic relations	?
Food chain	Length	Number of trophic levels
Sink web	?	?
Available energy	Amount	Body size
Self-organizing system	System attractor	Type (i.e. top predator)
Ecosystem trophic module or Photon shed	Extent	Area
		Volume

Coder	John Reap	Date	7/30/2007
Text Segment	Paragraphs: abstract - end	Type	Memo
Reference	Crutsinger, G.M., M.D. Collins, J.A. Fordyce, Z. Gompert, C.C. Nice and N.J. Sanders (2006) "Plant Genotypic Diversity Predicts Community Structure and Governs an Ecosystem Process." *Science* 313: 966-968.		

"…increasing population genotypic diversity…determined arthropod diversity and community structure and increased ANPP..."

Biodiversity, community, and ecosystem are the primary concepts present in this article. As observed in a number of other sources, biodiversity has the property of magnitude which varies by species number, number of genotypes and rarefied richness. Communities are assigned the property of structure which appears to vary by number of species per trophic level. The authors focus on the ecosystem property of productivity which they measure in aboveground net primary productivity (ANPP). The linkage between genotypic variation and the properties of communities and ecosystems is the main topic of this article.

Summarizing the authors' findings in terms of the generated codes, increasing the genotypic magnitude of biodiversity results in greater numbers of species at higher trophic levels and larger ecosystem ANPP. The focus on genetic diversity sets this paper apart from those that explore the relationship between species number and various ecosystem functions. It is interesting to note that a plant's ability to execute its life history in slightly different ways can make such a significant difference.

Potential Concepts: biodiversity (P: magnitude D: species number, number of genotypes, rarefied richness), community (P: structure D: number of species per trophic level), ecosystem (P: productivity D: ANPP),

Table 87: Summary of potential concepts, properties and dimensions for Crutsinger 2006

Concepts	Properties	Dimensions
Ecosystem	Productivity	Aboveground net primary production
Biodiversity	Magnitude	Species number
		Number of genotypes
		Rarefied richness
Community	Structure	Number of species per trophic level

Coder	John Reap	Date	7/31/2007
Text Segment	Paragraphs: abstract - end	Type	Memo
Reference	Damuth, John (1981) "Population density and body size in mammals." *Nature* 290: 699-700.		

"Density is related approximately reciprocally to individual metabolic requirements, indicating that the energy used by the local population of a species in the community is independent of body size."

Population density, size and metabolism are the obvious concepts in this short article. The author attempts to relate these three concepts, but he discovers that the total metabolic demands of a species' population are independent of body size. This result leads to a more profound concept.

Namely, the author encounters the idea of a metabolic constraint. He believes that, "The independence of species energy control and body size revealed by this reciprocal relationship implies…energy control of all species within similar bounds." He even ventures that a "general principle is involved." The mentioned reciprocal relationship relating population density (D), metabolic requirements (R) and body mass (W) is:

$$DR \propto W^{-0.75} W^{0.75}$$

This is a fascinating article, but it is short. I am not getting much in terms of properties and richness. He has a few concepts and an intriguing interpretation coupled to a compelling correlation. A search for other articles by Damuth is in order. The idea of a constraint might also be too definitive of a label for the relationship. It may be more an evolutionary tendency.

Potential Concepts: population density, size, metabolism, metabolic constraint

Table 88: Summary of potential concepts, properties and dimensions for Damuth 1981

Concepts	Properties	Dimensions
Population density	?	?
Size	?	?
Metabolism	?	?
Metabolic constraint	?	?

Coder	John Reap	Date	6/7/2007
Text Segment	Paragraphs: abstract to para. 2	Type	Memo
Reference	de Ruiter, Peter C., Anje-Margriet Neufel and John C. Moore. (1995) "Energetics, Patterns of Interaction Strengths, and Stability in Real Ecosystems" *Science* 269: 1257-1260.		

"…studying stability in ecosystems by looking at the structuring and the strengths of trophic interactions in community food webs."

Food web structure is one of the first and foremost concepts appearing in this work. The authors clearly present three of its properties: group number, interaction frequency and chain length. Group number clearly varies dimensionally from few to many, while interaction frequency would vary from seldom to often. Chain length varies between short and long. The authors also state that interaction strength is a property of food web structures, which one could dimension as low to high. However, at least two distinct approaches to quantifying this property have been attempted, and according to the authors, the use of Jacobian matrices (theoretical approach) and field / lab observations (experimental approach) have not been linked.

Connectivity, material / energy networks and related ideas are recurring in the biology literature. Such occurrences reinforce my belief that a principle related to connectivity will emerge. If it does, Jacobians may provide a useful way of quantifying and comparing ecological networks with industrial ones.

Potential Concepts: food web structure (P: group number D: few to many; P: interaction frequency D: seldom to often; P: chain length D: short to long; P: interaction strength D: low to high)

Text Segment	Paragraphs: 3-5	Type	Memo

"…we separately established the impacts of the interactions on food web stability by constructing Jacobian community matrices."

Food web stability is the most important idea presented in this paper. One might classify it as an independent concept, but it also nicely fits as a property of food web structure. Apparently, it is a dependent property. Its dimensional variation from high to low is not as important as its dependence upon other food web structural properties. The "pattern" of interaction strength is found to substantially influence stability. Pattern seems to be a dimension of interaction strength, though an ill defined dimension. The authors even admit that, "It is not yet clear how precisely the patterning relates to stability."

Potential Concepts: food web structure (P: group number D: few to many; P: interaction frequency D: seldom to often; P: chain length D: short to long; P: interaction strength D: low to high, by pattern)

Table 89: Summary of potential concepts, properties and dimensions for de Ruiter 1995

Concepts	Properties	Dimensions
Food web structure	Group number	Few to many
	Interaction frequency	Seldom to often
	Chain length	Short to long
	Interaction strength	Low to high
		By pattern

Coder	John Reap	Date	7/14/2007
Text Segment	Paragraphs: all	Type	Memo
Reference	D'Hont, S., P. Donaghay, J.C. Zachos, D. Luttenberg and M. Lindinger (1998) "Organic Carbon Fluxes and Ecological Recovery from the Cretaceous-Tertiary Mass Extinction". *Science* 282: 276-279.		

"…marine production may have recovered shortly after the mass extinction, but the structure of the open-ocean ecosystem did not fully recover for more than 3 million years."

This short article focuses on two properties of <u>ecosystems</u> – <u>structure</u> and <u>resilience</u>. As the quoted passage indicates, both properties are related. Examination of carbon 13 concentrations in deep ocean sediments reveals that less C^{13} was being transferred to ocean depths immediately following the C-T extinction. The authors believe larger organisms capable of transferring C^{13} to these depths were not present; therefore, recovery of ecosystem complexity (structure) was slower than production recovery following the extinction.

This work contains a few interesting dimensions for these commonly mentioned ecosystem properties. Structure is measured in terms of <u>carbon fluxes</u> while <u>carbon flux recovery rate</u> serves as a measure of ecosystem resilience.

Potential Concepts: ecosystem (P: structure D: carbon fluxes; P: resilience D: carbon flux recovery rate)

Table 90: Summary of potential concepts, properties and dimensions for D'Hont 1998

Concepts	Properties	Dimensions
Ecosystem	Structure	Carbon flux
	Resilience	Carbon flux recovery rate

Coder	John Reap	Date	6/9/2007
Text Segment	Paragraphs: entire article	Type	Memo
Reference	Doolittle, W. Ford. (2000) "Uprooting the Tree of Life" *Science* 282 (2): 1-6.		

"…the relationships among all living and extinct organisms could be represented as a single genealogical tree."

The author introduces concepts such as the genealogical tree, molecular phylogeny and the endosymbiont hypothesis. One could assign properties for the genealogical tree based on the way one relates organisms on the tree. The author mentions anatomical relationships and genetic relationships. Anatomic relations presumably are established based on physical and functional organism features while genetic relationships are measured with small subunit ribosomal RNA (SSU rRNA). Trees also have structure, though the dimensions for structure are not clear. This is a key point in this article, though. The genealogical "tree" may not have a tree structure; as a result of endosymbiosis or other gene exchange mechanisms, it may look like a network or a tree with fused branches.

Looking at the article again, I am not sure about molecular phylogeny and the endosymbiont hypothesis. They seem distinct, but properties are not forthcoming…

Overall, this article is poor in concepts, and those available do not seem of great utility.

Potential Concepts: genealogical tree (P: anatomical relationships D: physical and functional organism features; P: genetic relationships D: SSU rRNA; P: structure D:?), molecular phylogeny, endosymbiont hypothesis

Table 91: Summary of potential concepts, properties and dimensions for Doolittle 2000

Concepts	Properties	Dimensions
Genealogical tree	Anatomical relationships	Physical and functional organism features
	Genetic relationships	SSU rRNA
	Structure	?
Molecular phylogenty	?	?
Endosymbiont hypothesis	?	?

Coder	John Reap	Date	6/28/2007
Text Segment	Paragraphs: abstract - ?	Type	Memo
Reference	Dusenbery, D.B. (1998) "Fitness Landscapes for Effects of Shape on Chemotaxis and Other Behaviors of Bacteria" *Journal of Bacteriology* 180 (22): 5978-598.		

"Here, the relationship between bacterial size and movement cost is established and shown to fit the same allometric equation as that for size and movement cost in animals."

Fitness landscape and body shape are the main concepts appearing in this paper. Though central to the paper, the authors are not forthcoming with a definition for fitness landscapes. They seem to be contour plots of factors which affect the fitness of organisms. Body shape has properties such as surface area, diffusion efficiency, sinking influence, drag, gradient detection. All five vary dimensionally from low to high, and gradient detection also varies by type. The most interesting aspect of this paper is the author's use of an ellipsoid model to quantify and correlate values of these properties with fitness. He generates precise dimensions that optimize one or more of these properties and even calculates and "improvement factor."

Potential Concepts: fitness landscape, body shape (P: surface area D: low to high; P: diffusion efficiency D: low to high; P: sinking efficiency D: low to high; P: drag D: low to high; P: gradient detection D: low to high, type)

Table 92: Summary of potential concepts, properties and dimensions for Dusenbery 1998

Concepts	Properties	Dimensions
Body shape	Surface area	Low to high
	Diffusion efficiency	Low to high
	Sinking efficiency	Low to high
	Drag	Low to high
	Gradient detection	Low to high
		Type
Fitness landscape	?	?

Coder	John Reap	Date	4/28/2006
Text Segment	Paragraphs: abstract-3	Type	Memo
Reference	Ebenman, B. and T. Jonsson (2005). "Using community viability analysis to identify fragile systems and keystone species." Trends in Ecology & Evolution 20(10): 568-575.		

"Owing to interdependence…, the loss of one species can trigger a cascade of secondary extinctions… Community viability analysis…identify fragile community structures and keystone species and,…provide guidelines for conservation priorities."

In this quote from the abstract, the author is clearly stating his motivation and his contribution with the paper. He introduces a number of concepts in this abstract such as interdependence, extinction cascades and community viability. Interdependence is a word that applies in many contexts: society, economics and engineering to name a few. Functional interdependence within an engineered device is usually undesired; Suh, for example, frowns upon having a single feature perform many functions. In a more practical sense, interdependence means interactions, which complicates redesign or the development of open architectures, but I digress… Interdependence has at least two properties in this context – degree with dimensions of few or many interdependences and magnitude with dimensions of weak or strong interdependences. On second thought, community might be the concept with viability a property and with precarious to robust acting as its dimensions.

A community also has structure. Vermeij mentioned structure in relation to his principles and repetition of evolutionary innovations, but he mostly referred to physical structures. In this article, the structure is a web, hierarchy or some construction of interactions – links between nodes. Structure might be a property of community. But, what would its dimensions be? He later (p 572) defines interaction strength as the, "…direct effect of an individual of one species on the growth rate of another species."

Potential Concepts: interdependence (P: degree D: few to many interdependences; P: magnitude D: weak to strong interdependences), extinction cascades, community (P: viability D: precarious to robust; P: structure?)

"Community viability analysis…aim…is to predict the response of ecological communities to species loss, more specifically to assess the risk and extent of secondary extinctions."

In this set of paragraphs, the author discusses two types of community viability analyses and mentions a relation to population viability analysis. A static analysis focuses on link structures. This idea of link structures suggests a set of dimensions for the potential concept, structures; the dimensions could be <u>many to few links</u>. This property of structure seems related to the concept of interdependence. A dynamic analysis focuses on changes in species density through time and requires growth rate and "interaction strength" data. I think this idea of interaction strength is synonymous with the property magnitude of the concept interdependence. These ideas of links and interdependencies make me think of Graph Theory…, but I really do not understand graph theory. *If this leads somewhere, I might want to quantify it using graph theoretic notions.*

He introduces the idea of risk and extent when discussing extinctions. It occurs to me that these terms apply to the concept of extinction cascades. <u>Risk</u> and <u>extent</u> appear to be properties of an extinction cascade with dimensions of low to high and limited to extensive, respectively.

Potential Concepts: extinction cascades (P: risk D: low to high; P: extent D: limited to extensive), community (P: viability D: precarious to robust; P: structure D: number of links)

"…distribution of interaction strengths in natural communities is highly skewed towards weak interactions. …loss of species…increase the overall mean interactions strength in the community…could increase the risk of destabilization and subsequent collapses, because strong consumer –resource interactions tend to generate population fluctuations…making species more vulnerable to stochastic extinction…"

This point and the surrounding text are important. Here, we see multiple concepts converging to form clear relationships. We learn that community viability grows precarious, assuming a high risk of an extensive extinction cascade, when magnitudes of resource consumer interdependencies become high. We also may have a new dimension for structure; links can vary in arrangement from modular (compartmentalized) to integrated. It is argued that because modular structures decrease the magnitude of inter-module interdependences they "enhance food-web persistence."

Potential Concepts: community (P: viability D: precarious to robust; P: structure D: number of links D: modular to integrated arrangement)

Table 93: Summary of potential concepts, properties and dimensions for Ebenman 2005

Concepts	Properties	Dimensions
Interdependence	Degree	Few to Many
	Magnitude	Weak to Strong
Extinction Cascade	Risk	Low to High
	Extent	Limited to Extensive
Community	Viability	Precarious to Robust
	Structure	Number of links
		Modular to Integrated Arrangement

Coder	John Reap	Date	1/27/2007
Text Segment	Paragraphs: 1 - 10	Type	Memo
Reference	Emlen, D.J. (2001) "Costs and the Diversification of Exaggerated Animal Structures" *Science* 291(5508): 1534.		

"…costs of weapons production also may drive patterns of weapon evolution. …[suggesting] a mechanism for the diversification of exaggerated animal structures that focuses on the costs, rather than the benefits…"

Though the author uses the word "costs," most of his article discusses aspects of <u>resource allocation</u>. His examples and data correlations show the consequences for other organism components when one feature is given a preferential allocation of resources. Costs are usually monetary in engineering, but resources include energy, materials and time. Given that this author is discussing a physical system, not an economic one, it is reasonable to think in terms of resources. <u>Diversity</u> is a related concept in this article. Beetles achieve diverse horn formations by allocating limited resources in different ways. Perhaps, then, resource allocation is a property of diversity having a dimensional range of <u>even to particular</u>.

<u>Environmental influence</u> is also a potential concept appearing in the first ten paragraphs. The author mentions <u>functional costs</u> that vary with the environment. For example, he reasons that nocturnal beetles would tend not to place a horn in a position that draws resources away from its eyes because this would increase the "costs" associated with conducting many of its activities. Functional cost seems to be a type of environmental influence, a property of environmental influence. It seems reasonable to vary it between <u>high and low</u>, though units seem uncertain.

Potential Concepts: diversity (P: resource allocation D: even to particular), environmental influence (P: functional cost D: high to low)

Text Segment	Paragraphs: 11-12	Type	Memo

"…functional costs may help explain the evolution of a variety of exaggerated structures…when two conditions are met: (i) the enlarged structures are produced coincident with the rest of adult morphology…and (ii) resources are limited for at least part of this period."

The author's conditions suggest a second dimension for resource allocation. It may occur simultaneously or sequentially. Resource abundance also seems to play a part. He clearly believes resource limitations influence the evolution of exaggerated structures. They may vary between abundant and scarce.

One might than recast this authors conclusions in the follow way. In the presence of high functional costs imposed by environmental conditions, a diversity of responses occurs when scarce resources are unevenly and simultaneously allocated. Hmm…

Potential Concepts: diversity (P: resource allocation D: even to particular, D: simultaneous or sequential; P: resource abundance D: abundant to scarce),

Table 94: Summary of potential concepts, properties and dimensions for Emlen 2001

Concepts	Properties	Dimensions
Diversity	Resource allocation	Even to particular
		Simultaneous to sequential
	Resource abundance	Abundant to scarce
Environmental Influence	Functional cost	High to low

Coder	John Reap	Date	6/30/2007
Text Segment	Paragraphs: abstract - 3	Type	Memo
Reference	Wright, Justin P. and Clive G. Jones (2006) "The Concept of Organisms as Ecosystem Engineers Ten Years On: Progress, Limitations, and Challenges." *BioScience* 56 (3): 203-209.		

"…many organisms alter physical structure and change chemical reactivity in ways that are independent of their assimilatory or dissimilatory influence."

This quotation defines the ecosystem engineering concept. It contains its influence property and provides chemical reactivity and physical structure changes as two general types of influence. The abstract and opening paragraphs are not particularly rich in other concepts, properties or dimensions.

It is interesting to note that the authors believe the traditionally important concepts in ecology are competition, predation, metabolically associated nutrient flows and metabolically associated energy flows. They seem ready to rank ecosystem engineering in the same class.

Potential Concepts: ecosystem engineer (P: influence D: type), competition, predation, metabolically associated nutrient flows, metabolically associated energy flows

Text Segment	Paragraphs: 12-13	Type	Memo

In these later paragraphs, three interesting concepts emerge in relation to ecosystem engineers. Community assemblages seem to be combinations of interacting organisms. Environmental gradients would presumably be changes in biotic or physical elements of the landscape relative to distance or time. Niche construction appears to relate to the order in which one builds a community of organisms. Though lacking properties and dimensions, these concepts are interesting because they remind me of questions related to industrial eco-park and ecosystem assembly. Can one think of industrial ecological gradients that favor particular assemblages of industries? How would one construct an industrial ecological niche? Can the related biological concepts inform answers to such industrial questions?

Potential Concepts: ecosystem engineer (P: influence D: type), competition, predation, metabolically associated nutrient flows, metabolically associated energy flows, community assemblages, environmental gradients, niche construction

Table 95: Summary of potential concepts, properties and dimensions for Wright 2006

Concepts	Properties	Dimensions
Ecosystem engineer	Influence	Type (i.e. chemical reactivity changes, physical structure changes)
Competition	?	?
Predation	?	?
Metabolically associated nutrient flows	?	?
Metabolically associated energy flows	?	?
Community assemblages	?	?
Environmental gradients	?	?
Niche construction	?	?

Coder	John Reap	Date	6/5/2007
Text Segment	Paragraphs: abstract to para. 4	Type	Memo
Reference	Hansen, W.R. and K. Autumn (2005) "Evidence for self-cleaning in gecko setae" *Proceedings of the National Academy of Sciences* 102 (2): 385-389.		

"How geckos manage to keep their feet clean while walking about with sticky toes has remained a puzzle until now."

Self-cleaning and adhesion are the two main concepts in this paper. In fact, the paper is built around an effort to understand the unlikely occurrence of both behaviors on gecko feet. Self-cleaning possesses the property of assistance. The authors note that other self cleaning structures require the input of water, animal secretions or specific mechanical actions such as grooming, but the geckos' feet remain clean without specific actions. These facts suggest the existence of at least two dimensions for assistance. The amount of assistance varies from none to specific cleaning action; assistance also varies by type. Adhesion's properties are not clear to me. One could describe the types of adhesion; for example, Van der Waal's forces are responsible for gecko feet adhesion. But, this seems less than satisfactory.

The authors also introduce concepts such as energetic disequilibrium and microstructure in the first sections. They discuss lamellar pads formed from micro-scale seta that branch into even smaller spatulae. From such descriptions, it is clear that hierarchy is a property of microstructure in this context, though the dimensions of hierarchy are not obvious. Potentially, one could use level or spatial increments. Energetic disequilibrium receives more attention in later sections.

Potential Concepts: self-cleaning (P: assistance D: none to specific cleaning action, D: type (i.e. water, secretions, grooming, etc.)), adhesion, energetic disequilibrium, microstructure (P: hierarchy D: ?)

Text Segment	Paragraphs: 12-14	Type	Memo

"…measurements of setal and spatular force…with new theoretical results suggest…simple shapes can be used to model the contact mechanics of spatulae."

In these paragraphs, the authors develop a force balance that purports to explain the self-cleaning behavior of gecko feet. It quantifies the concept of energetic disequilibrium, but it does not explain it.

Text Segment	Paragraphs: 15 - end	Type	Memo

"Roughness…results in surfaces that are self-cleaning in the presence of water droplets."

<u>Roughness, hydrophobicity and waxiness</u> all appear as properties of microstructures that influence self-cleaning behavior. The authors specifically dimension roughness from <u>low to high</u>, observing that "micro- or nano-rough topology…reduces adhesion with solid and liquid surfaces alike." They note that high hydrophobicity appears to be an important characteristic of self-cleaning surfaces; thus, the dimensions of <u>low to high</u> seem appropriate.

They list a set of "design principles" for "passive, dry self-cleaning adhesive nanostructure[s]" worth noting.

(i) *surface area smaller than that of dirt particles*

(ii) *made of hardy, relatively nontacky materials, and*

(iii) *having low surface energy ([lambda], one-half the energy of cohesion)…*

And, they conclude with a short discussion of a concept one might call the <u>adhesion vs. self-cleaning tradeoff</u>. For arrays of adhesive nano-hairs, high surface energy might promote better adhesion, but it would also decrease or eliminate self-cleaning and anti-self-adhesion properties. Therefore, they suggest that evolution has balanced the parameters of the gecko's foot between adhesion and a state of being maintenance free.

Potential Concepts: self-cleaning (P: assistance D: none to specific cleaning action, D: type (i.e. water, secretions, grooming, etc.)), adhesion, energetic disequilibrium, microstructure (P: hierarchy D: ?; P: roughness D: low to high; P: hydrophobicity D: low to high; P: waxiness D:?), adhesion vs. self-cleaning tradeoff

Table 96: Summary of potential concepts, properties and dimensions for Hansen 2005

Concepts	Properties	Dimensions
Self Cleaning	Assistance	None to specific cleaning action
		Type (i.e. water, secretions, grooming, etc.)
Adhesion	?	?
Energetic disequilibrium	?	?
Microstructure	Hierarchy	?
	Roughness	Low to high
	Hydrophobicity	Low to high
	Waxiness	?
Adhesion vs. self-cleaning tradeoff	?	?

Coder	John Reap	Date	6/21/2007
Text Segment	Paragraphs: 1-22	Type	Memo
Reference	Harold, Franklin M. (2005) "Molecules into Cells: Specifying Spatial ARchitecture" *Microbiology and Molecular Biology Reviews* 69 (4): 544-564.		

"Architecture is what ultimately distinguishes a living cell from a soup of the chemicals..."

In a sense, every concept in this paper relates to the concept of a <u>cell</u>, but to achieve finer coding granularity, I will leave this relationship tacit. After the cell, the next concept to appear is <u>architecture</u>. Architecture seems to have the properties of <u>spatial organization</u>, <u>functional coherence</u> and <u>competitive value</u>. However, the dimensions of these properties are not clear, and moreover, they might be independent concepts.

He also introduces the idea of <u>self-organization</u> and related concepts such as <u>self-assembly</u>, <u>self-construction</u> and <u>emergence</u>. He defines self-organization as the emergence of larger scale order from small scale interactions guided by local rules. This is a common definition for self-organization. I should obtain the cited papers discussing larger scale examples of self-organization. The author attributes the property of <u>dynamics</u> to self-assembly and goes on to cite examples of bio-molecules that assemble themselves into different shapes when combined. It is not clear to me what static self-assembly would be given the cited examples. An uncommon observation is made during his discuss of self-assembly. He notes that, "…Few if any of the complex internal structures can arise solely in obedience to local rules…" Later, he cites a cellular principle originally observed by Lionel Jaffe. This principle states that cellular development usually moves inward from the outside, highlighting the importance of environmental signals and lending credence to arguments that local rules have limited control.

Potential Concepts: cell, architecture (P: spatial organization D: ?; P: functional coherence D:?; P: competitive value D: ?), self-organization, self-assembly (P: dynamic D:?), self-construction, emergence

Text Segment	Paragraphs: 23-35	Type	Memo

"As far as we know, there is no other way to generate order on the cellular scale: it must be built upon existing order."

As I read the above quoted sentence, it occurred to me that the <u>order from order</u> concept appeared many times and in many guises in this paper. In paragraph 26, he states, "…The general rule is that membranes grow by enlargement of an existing membrane," and in paragraph 30, he observes that the location of protein "landmarks" is a result of, "…the continuity of cell structure." He repeatedly refers to spatial positioning and sequence of events in connection with inherited order; so, <u>spatial</u> and <u>temporal</u> seem to be properties of order from order. The mentions multiple spatial scales multiple times, which suggests that the spatial property of order from order varies dimensionally by <u>scale</u>. <u>Templet</u>, a source for configuration information, seems to be a related concept. The author contends that the existence of a templet in the form of a mother cell provides the original order from which a daughter cell's order comes. According to a dictionary of technical terms, templet is a synonym for template; I will use the later.

Potential Concepts: order from order (P: spatial D: scale; P: temporal D: ?), template

Text Segment	Paragraphs: 36-66	Type	Memo

"…spatially extended influence seems to be called for, most probably of a kind traditionally associated with the idea of a field."

The author conjures the <u>morphogenetic field</u> concept to explain his thoughts about spatial organization in these paragraphs. He defines morphogenetic fields as:

> <u>Morphogenetic field</u> – "…a discrete territory within which genetic information is coherently translated into three-dimensional architecture."

Generation of these fields figures prominently in his discussion. One might say that <u>generation</u> is a property of morphogenetic fields that varies between <u>external and internal</u>. Hydrostatic pressure (turgor) is an example of an externally generated field while action by a cell's cytoskeleton would count as an internal one.

He closes this set of paragraphs by stating a general set of features for prokaryotic cells, but I find it difficult to generalize them.

Potential Concepts: morphogenetic field (P: generation D: external and internal)

Text Segment	Paragraphs: 81-98	Type	Memo

"…self-organizing chemistry takes place in a cell, it comes under guidance and constraint from the cellular system as a whole."

In these closing paragraphs, one finds ideas commonly encountered when discussing hierarchies. Higher organizational levels constrain lower organization levels. The author's statements about self-organizing chemistry within a cell serve as an example. He views these cellular scale constraints as "organizing principles" and lists them:

- Spatial markers
- Vectorial physiology
- Gradient fields
- Physical forces

These organizing principles are casual agents for the spatial organization of cellular architecture, providing a dimension for this previously stated property.

Time is another aspect of cellular architecture occurring repeatedly in this paper. Architecture in cells is viewed as transient; so, existence time is one of its properties. It seems reasonable that it would vary dimensionally from short to long.

Potential Concepts: cell, architecture (P: spatial organization D: casual agents; P: functional coherence D:?; P: competitive value D: ?; P: existence time D: short to long), self-organization, self-assembly (P: dynamic D:?), self-construction, emergence

Table 97: Summary of potential concepts, properties and dimensions for Harold 2005

Concepts	Properties	Dimensions
Cell	?	?
Architecture	Spatial organization	Casual agents (spatial markers, vectoral physiology, gradient fields and physical forces)
	Functional coherence	?
	Competitive value	?
	Existence time	Short to long
Self-organization	Dynamic	?
Self-assembly	?	?
Self-construction	?	?
Emergence	?	?
Order from order	Spatial	Scale
	Temporal	?
Template	?	?
Morphogenetic Field	Generation	External to internal

Coder	John Reap	Date	6/30/2007
Text Segment	Paragraphs: abstract - 11	Type	Memo
Reference	Hastings, A., J.E. Byers, J.A. Crooks, K. Cuddington, C.G. Jones, J.G. Lambrinos, T.S. Talley and W.G. Wilson (2007) "Ecosystem engineering in space and time" *Ecology Letters* 10: 153-164.		

"…ecosystem engineering concept focuses on how organisms physically change the abiotic environment and how this feeds back to the biota."

In the abstract, the authors name two important properties of the ecosystem engineering concept: influence and duration. Ecosystem engineers are organisms that affect the physical environment in which other organisms live. These effects are as diverse as the organisms that create them; so, influence varies dimensionally by type. They can last from seconds to millions of years (i.e. coral reefs). There are also two different types of ecosystem engineers: autogenic and allogenic. The bodies of autogenic engineers change their environments while allogenic ones modify other living or non-living material.

Interspecific interactions also appear as a potentially distinct concept within the context of ecological engineering. They have the properties of engineered and non-engineered. The associated dimensions are not clear.

Potential Concepts: ecosystem engineering (P: influence D: type; P: type D: autogenic or allogenic ;P: Duration D: seconds to millions of years), interspecific interactions (P: engineered D: ?; P: non-engineered D: ?)

Text Segment	Paragraphs: 12 - 17	Type	Memo

"Ecosystem engineers can have dramatic effects at both large and small spatial scales, where scale is defined relative to the engineer."

Later, the idea of space enters into the discussion. Spatial extent is another property of ecosystem engineering that further explains and defines the concept. The stated excerpt reveals this property. Provided tables give dimensions that vary between centimeters and thousands of kilometers; though, as the quotation reveals, dimensions are best measured relative to the organism.

One could also dimension the duration of an ecosystem engineer's work with a decay rate. The decay would be the rate at which an engineered environment returns to its original state.

Potential Concepts: ecosystem engineering (P: influence D: Type; P: type D: autogenic or allogenic ; P: duration D: seconds to millions of years; P: spatial extent D: centimeters to thousands of kilometers), interspecific interactions (P: engineered D: ?; P: non-engineered D: ?)

Text Segment	p. 160	Type	Memo

"Ecosystem engineers can have dramatic effects at both large and small spatial scales, where scale is defined relative to the engineer."

This page intersects ecosystem engineering with a number of established concepts in biology and ecology such as diversity, food webs, succession, biogeochemical processes and inter-food web exchanges. The authors believe that ecosystem engineering increases diversity at large spatial scales. It is believed that they also affect food web connectivity and partially control flows of energy, material and information between food webs. They also might "facilitate" succession.

Potential Concepts: ecosystem engineering (P: influence D: Type; P: type D: autogenic or allogenic ; P: duration D: seconds to millions of years; P: spatial extent D:

centimeters to thousands of kilometers), interspecific interactions (P: engineered D: ?; P: non-engineered D: ?), diversity, food webs, inter-food web exchanges, succession, biogeochemical processes.

Table 98: Summary of potential concepts, properties and dimensions for Hastings 2007

Concepts	Properties	Dimensions
Ecosystem engineer	Influence	Type
	Type	Autogenic or allogenic
	Duration	Seconds to millions of years
	Spatial extent	Centimeters to thousands of kilometers
Interspecific interactions	Engineered	?
	Non-engineered	?
Diversity	?	?
Food webs	?	?
Inter-food web exchanges	?	?
Succession	?	?
Biogeochemical processes	?	?

Coder	John Reap	Date	7/18/2007
Text Segment	Paragraphs: all	Type	Memo
Reference	Hector, A. and R. Bagchi (2007) "Biodiversity and ecosystem functionality." *Nature* 448: 188-191.		

"…as more ecosystem processes were included in our analysis, more species were found to affect overall functioning."

The concepts of ecosystem and biodiversity dominate this article. The primary property of ecosystems considered in this article is function. It varies dimensionally by type (i.e. biomass production, soil nitrogen, etc.) and number. Redundancy also seems to be a property attributed to ecosystems. Biodiversity's property of magnitude varies dimensionally by number of species. The idea of saturation also appears in relation to ecosystems and the influence of biodiversity.

According to the author's analysis, a greater magnitude of biodiversity is required to support increasing numbers of ecosystem functions. A saturating affect is observed, however. The rate of increase in the number of required species eventually decreases with increasing numbers of functions. The authors' findings indicate that more than one species is responsible for each function, which suggests a level of redundancy in ecosystems.

Potential Concepts: ecosystem (P: function D: type, number; P: redundancy D: ?), Biodiversity (P: magnitude D: number of species)

Table 99: Summary of potential concepts, properties and dimensions for Hector 2007

Concepts	Properties	Dimensions
Ecosystem	Function	Type
		Number
	Redundancy	?
Biodiversity	Magnitude	Number of species

Coder	John Reap	Date	6/20/2007
Text Segment	Paragraphs: abstract - 9	Type	Memo
Reference	Herre, E.A. (1999) "The evolution of mutualisms: exploring the paths between conflict and cooperation" *Trends in Evolution and Ecology* 14 (2): 49-52.		

"…mutualisms are ubiquitous, often ecologically dominant, and profoundly influential..."

This article reiterates and adds to information about the mutualism concept. It defines mutualisms, "as reciprocal exploitations that nonetheless provide net benefits to each partner." One partner is usually referred to as the host while the other is the symbiont. One learns that mutualisms have the property of "range" or degree which varies from "diffuse and indirect" to integrated. Stability is another property mentioned in the context of mutualism. The authors provide a list of factors favoring partnerships:

- "…passage of symbionts from parent to offspring…"
- Genetic homogeneity of symbionts in a host
- Repeated interactions between potential partners
- "…restricted options outside the relationship…"

Host and symbiont might be thought of as concepts unto themselves. Symbionts seem to possess the property of diversity. Diversity would reasonably vary dimensionally from low to high.

Potential Concepts: mutualism (P: degree D: "diffuse and indirect" to integrated; P: stability D: ?)

Text Segment	Paragraphs: 13-15	Type	Memo

"Several studies have documented that net costs and benefits can vary..."

The cost-benefit analysis concept appears in this article. Properties and dimensions are not apparent, but the author does state four factors that can influence costs and benefits for partners in a symbiotic relationship.

- Abundance and influence of third parties
- Changes in host density patterns affecting transmission
- Resource availability
- "…variation in physical conditions…"

A concept called Hamilton's rule is mentioned in the conclusion. This rule might be worth investigating.

Table 100: Summary of potential concepts, properties and dimensions for Herre 1999

Concepts	Properties	Dimensions
Mutualism	Degree	"diffuse and indirect" to integrated
	Stability	?
Host	?	?
Symbiont	Diversity	Low to high
Cost-benefit analysis	?	?
Hamilton's Rule	?	?

Coder	John Reap	Date	7/16/2007
Text Segment	Paragraphs: Table 1, p. 448-459	Type	Memo
Reference	Holling, C.S. (1992) "Cross-Scale Morphology, Geometry and Dynamics of Ecosystems." *Ecological Monographs* 62 (4): 447-502.		

"…All terrestrial ecosystems are controlled and organized by a small set of key plant, animal and abiotic processes."

These key plant, animal and abiotic processes are later labeled critical structuring processes. In the author's guiding table and surrounding sections, it is clear that these critical processes possess the property of periodicity which varies dimensionally from short to long. The value of short or long is set in relation to other system processes. If one considers dominant tree species, the longest period for a process would be set by tree life spans, but if one adds successional dynamics, periods might last centuries.

The author introduces the idea of entrainment as a consequence of these critical structuring processes. He argues that many other ecosystem variables and processes would be influenced by critical structuring processes. He further argues that nested hierarchies observed in the landscape are a consequence of entrainment and that body-mass discontinuities can serve as a means of detecting them.

Potential Concepts: critical structuring processes (P: periodicity D: short to long), nested hierarchies

Text Segment	Paragraphs: Table 1, p. 460-474	Type	Memo

"…geometry of landscapes and ecosystems is organized into a small number of quanta with distinct architectural attributes, and these quanta shape the morphology of animals."

As this quotation suggests, these sections add the property of geometry to the ecosystem concept. Holling uniquely quantifies ecosystem geometry using the dimension of quanta.

These sections also witness the introduction of the home range concept. It possesses the properties of size and productivity, both of which vary dimensionally from low to high. The related concept of sampling grain also appears in these sections. This concept attempts to label what the author believes to be a crucial interaction between organisms and their respective environments. An organism's size allows it to experience an ecosystem's geometry in a particular way. For example, dimensions of sand grains are important for small organisms such as sand flees, but they are far less important for a human walking on a beach. Size, therefore, seems a reasonable property of sampling grain that varies dimensionally by grain size. Grain size would also seem to set the increment for measuring a home range. One might think of the discretization of a home range which varies dimensionally by grain size.

Using the presented codes to represent the author's conclusions, home range sizes are small when productivity is high.

Potential Concepts: critical structuring processes (P: periodicity D: short to long; P: geometry D: quanta), nested hierarchies, home range (P: size D: low to high; P: productivity D: low to high; P: discretization D: grain size), sampling grain (P: size D: grain size)

Text Segment	Paragraphs: Table 1, p. 480-482	Type	Memo

"…the literature on ecosystems has led to major revisions in…succession as being a highly ordered sequence of species assemblages moving toward a sustained climax..."

Succession, an ecological mainstay, surfaces toward the end of Holling's lengthy paper. He presents this venerable idea as repeating series of transitions beginning with exploitation, proceeding through conservation to release, reorganization and finally back to exploitation. In other words, he provides the property of stage for succession and redefines its dimensions. His statements about the transition from conservation to release indicate that an ecosystem's property of structure can vary dimensionally from under to over connected. He believes that an ecosystem with an over connected structure is brittle and prone to collapse or "release."

Potential Concepts: critical structuring processes (P: periodicity D: short to long; P: geometry D: quanta), nested hierarchies, home range (P: size D: low to high; P: productivity D: low to high; P: discretization D: grain size), sampling grain (P: size D: grain size), succession (P: stage D: exploitation, conservation, release, reorganization), ecosystem (P: structure D: under or over connected)

Table 101: Summary of potential concepts, properties and dimensions for Hollings 1992

Concepts	Properties	Dimensions
Critical structuring processes	Periodicity	Short to long
	Geometry	Quanta
Nested hierarchies	?	?
Home range	Size	Low to high
	Productivity	Low to high
	Discretization	Grain size
Sampling grain	Size	Grain size
Succession	Stage	Exploitation, conservation, release, reorganization
Ecosystem	Structure	Under or over connected

Coder	John Reap	Date	7/6/2007
Text Segment	Paragraphs: all	Type	Memo
Reference	Hooker, Henry D. (1917) "Liebig's Law of the Minimum in Relation to General Biological Problems". *Science* 46 (1183): 197-204.		

"…Law of the Minimum is a *universal* law, affecting not merely the concentration of reacting substances, but all factors that in any way influence a reaction or process."

Using examples from chemistry, algebra, agricultural and botany, Hooker attempts to state the essence of <u>Liebig's Law of the Minimum</u>. At its core, this law states that processes are constrained by a limiting factor. Removing one limitation simply provides a system space to encounter another. Two of his examples illustrate his understanding of the law:

> *…the yield of any crop always depends on the nutritive constituent which is present in minimum amount.*

> *…the rate of the process is limited by the pace of the 'slowest' factor.*

Liebig's Law boils down to the folksy notion that "a chain is no stronger than its weakest link."

Many rules have exceptions, and Liebig's is not exception to this rule. Hooker labels the process by which abundances in some factors are used to overcome limitations in others as <u>compensation</u>. One property of compensation is <u>type</u> which varies dimensionally by type – adaptation, etc.

Potential Concepts: Liebig's Law, compensation (P: type D: adaptation)

Table 102: Summary of potential concepts, properties and dimensions for Hooker 1917

Concepts	Properties	Dimensions
Liebig’s Law	?	?
Compensation	Type	Adaptation, etc.

Coder	John Reap	Date	7/2/2007
Text Segment	Paragraphs: abstract – p.7	Type	Memo
Reference	Hooper, D.U., F.S. Chapin III, J.J. Ewel, A. Hector, P. Inchausti, S. Lavorel, et al. (2005) "Effects of Biodiversity on Ecosystem Functioning A Consensus of Current Knowledge" *Ecological Monographs* 75(1): 3-35.		

"…ecosystem properties depend greatly on biodiversity in terms of the functional characteristics or organisms…and the distribution and abundance of those organisms over space and time."

Rich in concepts and biological detail, this paper unites a number of diversity related themes in one document. Multiple forms of biodiversity appear in this lengthy yet well written paper. The authors define this concept as follows:

> *Biodiversity can be described in terms of numbers of entities (how many genotypes, species or ecosystems), the evenness of their distribution, the differences in their functional traits…, and their interactions.*

It seems reasonable to consider each form a property, making genetic, taxonomic, functional and structural properties of biodiversity. Number of species provides one dimension for taxonomic biodiversity; relative abundance and distribution evenness provide two more. Functional biodiversity varies dimensionally by fulfilled roles. Dimensions for genetic and structural biodiversity are not apparent, though some means of identifying chromosomal similarity is a likely way of dimensioning genetic biodiversity.

The tone adopted by the author leads one to believe that biodiversity is often the cause of an ecosystem response or is responsible for a set of ecosystem properties. The ecosystem property concept is defined by properties such as compartment size (amount of material stored in an ecosystem) productivity and nutrient retention. They dimensionally vary from low to high. Stability and robustness both appear in these early paragraphs, but the authors provide a better discussion in later sections.

The species interaction concept receives a small though significant amount of coverage in the abstract. One learns that the properties of this concept are the types of interactions: competition, facilitation, mutualism, disease and predation. All of these can vary from low to high.

Other mentioned concepts include: dominant species, keystone species and ecological engineers.

Potential Concepts: biodiversity (P: genetic D: ?; P: taxonomic D: number of species, relative abundance, distribution evenness; P: functional D: fulfilled roles; P: structural D: ?), ecosystem properties (P: compartment size D: low to high; P: productivity D: low to high; P: nutrient retention D: low to high), species interaction (P: competition D: low to high; P: facilitation D: low to high; P: mutualism D: low to high; P: disease D: low to high; P: predation D: low to high), dominant species, keystone species, ecological engineers

Text Segment	Pages: 8 – 11	Type	Memo

"…species or functional richness could increase ecosystem properties through positive interactions among species. Complementarity and facilitation are the two primary mechanisms…"

These text segments do not contain new overt concepts as much as explain a relationship between those previously introduced. Increases in taxonomic and functional biodiversity influence the properties of species interactions. Specifically, competition may be reduced through niche partitioning which in turn allows a more complete utilization of resources. As a result, the ecosystem properties of productivity and nutrient retention increase. Alternatively, a diverse set of organisms might increase facilitation interactions which improve the number, amount or rate of environmental resources available. Such activities tend to increase the ecosystem property of compartment size. Facilitation might also give rise to new functional roles; diversity might catalyze diversity, leading to further increases in ecosystem properties. It should also be noted that changes in structural biodiversity may also influence ecosystem properties.

Stated succinctly, increasing biodiversity may allow decreasing competition and increasing facilitation which in turn raises ecosystem productivity, material retention and compartment size.

Potential Concepts: biodiversity (P: genetic D: ?; P: taxonomic D: number of species, relative abundance, distribution evenness; P: functional D: fulfilled roles; P: structural D: ?), ecosystem properties (P: compartment size D: low to high; P: productivity D: low to high; P: nutrient retention D: low to high), species interaction (P: competition D: low to high; P: facilitation D: low to high; P: mutualism D: low to high; P: disease D: low to high; P: predation D: low to high), dominant species, keystone species, ecological engineers

Text Segment	Pages: 13	Type	Memo

"Evenness of the plant community also could lead to increased productivity with increasing species richness…"

Ecosystem responses to biodiversity discussed in the previous section may depend upon a high degree of taxonomic evenness.

Another dimension for functional diversity is found on this page. It is observed that functional diversity varies from <u>similar to distinct</u>. Apparently, the presence of organisms with distinct functional roles is more likely to promote low competition and high facilitation.

Potential Concepts: biodiversity (P: genetic D: ?; P: taxonomic D: number of species, relative abundance, distribution evenness; P: functional D: fulfilled roles, similar to distinct; P: structural D: ?), ecosystem properties (P: compartment size D: low to high; P: productivity D: low to high; P: nutrient retention D: low to high), species interaction (P: competition D: low to high; P: facilitation D: low to high; P: mutualism D: low to high; P: disease D: low to high; P: predation D: low to high), dominant species, keystone species, ecological engineers

Text Segment	Pages: 15-19	Type	Memo

"…'stability' in biotic communities…refers to…resistance to disturbance, resilience to disturbance, temporal variability in response to fluctuating abiotic conditions, and spatial variability in response to differences in either abiotic or conditions or the biotic community."

<u>Stability</u> is another property of the ecosystem property concept that captures a community's or an ecosystem's response to abiotic or biotic changes. It varies dimensionally from <u>chaotic to constant</u>. Previously encountered concepts such as <u>resilience</u> and <u>resistance</u> also appear. Resistance may be synonymous with robustness in this context. However, the means of achieving stability and the relationship with

biodiversity make these pages interesting. Diversity in organism response and redundancy in functional traits tend to instill stability in ecosystem properties.

The “Shannon-Wiener index of diversity (H’)” is a metric for ecosystem diversity. I need to obtain a definition of this metric; it may be possible to adapt it to industrial situations.

Potential Concepts: biodiversity (P: genetic D: ?; P: taxonomic D: number of species, relative abundance, distribution evenness; P: functional D: fulfilled roles, similar to distinct; P: structural D: ?), ecosystem properties (P: compartment size D: low to high; P: productivity D: low to high; P: nutrient retention D: low to high; P: stability D: chaotic to constant), robustness, species interaction (P: competition D: low to high; P: facilitation D: low to high; P: mutualism D: low to high; P: disease D: low to high; P: predation D: low to high), dominant species, keystone species, ecological engineers

Table 103: Summary of potential concepts, properties and dimensions for Hooper 2005

Concepts	Properties	Dimensions
Biodiversity	Genetic	?
	Taxonomic	Number of species
		Relative abundance
		Distribution evenness
	Functional	Fulfilled roles
		Similar to distinct
	Structural	?
Ecosystem properties	Compartment size	Low to high
	Productivity	Low to high
	Nutrient retention	Low to high
	Stability	Chaotic to constant
Robustness	?	?
Species interaction	Competition	Low to high
	Facilitation	Low to high
	Mutualism	Low to high
	Disease	Low to high
	Predation	Low to high
Dominant species	?	?
Keystone species	?	?
Ecological engineers	?	?

Coder	John Reap	Date	6/18/2007
Text Segment	Entire article	Type	Memo
Reference	Hughes, Terry P., D.R. Bellwood, C.S. Folke, L.J. McCook and J.M. Pandolfi (2000) "No-take areas, herbivory and coral reef resilience" *Trends in Ecology and Evolution* 22 (1): 1-3.		

This short article mentions previously encountered concepts such as food webs and ecosystem function. It adds a new food web property – distortion. Distortion has dimensions of extent and type. The types of distortions mentioned relate to either harvesting or nutrient addition. Collapse of reef food webs by nutrient addition reminds me of the problems encountered by recyclers in Germany when the federal government mandated recycling. An excess of "nutrients" in the industrial system caused problems.

Biomass production, which varies dimensionally from low to high, is one property of ecosystem function; it is one type of function. They observe that protected coral reefs produce more biomass than unprotected ones, or at least, they observe that biomass stocks are higher on protected reefs. Resilience also seems to be a property of ecosystem function. It too varies from low to high, but the authors do not provide much detail about this point.

Potential Concepts: food web (P: distortion D: type, extent), ecosystem function (P: biomass production D: low to high; P: resilience D: low to high)

Table 104: Summary of potential concepts, properties and dimensions for Hughes 2000

Concepts	Properties	Dimensions
Food web	Distortion	Type (harvesting, nutrient input)
		Extent
Ecosystem function	Biomass production	Low to high
	Resilience	Low to high

Coder	John Reap	Date	7/13/2007
Text Segment	Paragraphs: abstract-3	Type	Memo
Reference	Jablonski, David "The interplay of physical and biotic forces in macroevolution" in *Evolution on Earth: The Impact of the Physical Environment*. (2003) L.J. Rothschild and A.M. Lister Eds. Academic Press: Amsterdam.		

"Large scale evolutionary patterns are shaped by...physical, intrinsic biotic and extrinsic biotic factors…"

Concepts such as macroevolution and evolutionary modifiers are present in the abstract. Macroevolution is defined as evolution "above the species level." It seems to have the dynamics property that varies dimensionally by extinction rate and origination rate. Evolutionary modifiers have properties such as physical influence and biotic influence. Each varies dimensionally by type, and biotic influence is also either intrinsic or extrinsic.

Potential Concepts: macroevolution (P: dynamics D: extinction rate, origination rate), evolutionary modifiers (P: physical influence D: type; P: biotic influence D: type, intrinsic or extrinsic)

Text Segment	Paragraphs: 4-18	Type	Memo

"A huge array of intrinsic biotic factors have been implicated in differential extinction and speciation probabilities"

This set of paragraphs lists different types of biotic influences. Intrinsic biotic factors include: body size, mobility, metabolic rate, physiological tolerance limits, feeding type, and dispersal ability. Extrinsic biotic factors include: incumbency, predation and competition.

Potential Concepts: macroevolution (P: dynamics D: extinction rate, origination rate), evolutionary modifiers (P: physical influence D: type; P: biotic influence D: type, intrinsic or extrinsic)

Text Segment	Page 244-246	Type	Memo

It may be worth investigating work on "reef gaps" and the recovery of reefs. Recover in general might be an area of ecology / biology that might contain some insights into the matter of principles for sustainability.

Potential Concepts: macroevolution (P: dynamics D: extinction rate, origination rate), evolutionary modifiers (P: physical influence D: type; P: biotic influence D: type, intrinsic or extrinsic)

Table 105: Summary of potential concepts, properties and dimensions for Jablonski 2003

Concepts	Properties	Dimensions
Macroevolution	Dynamics	Extinction rate
		Origination rate
Evolutionary modifiers	Physical influence	Type
	Biotic influence	Type (i.e. intrinsic: body size, mobility, metabolic rate, physiological tolerance limits, feeding type, and dispersal ability; extrinsic: incumbency, predation and competition)
		Intrinsic or extrinsic

Coder	John Reap	Date	7/5/2007
Text Segment	Paragraphs: abstract	Type	Memo
Reference	Jones, C.G., J.H. Lawton and M. Shachak (1994) "Organisms as ecosystem engineers" *Oikos* 69: 373-386.		

"Ecosystem engineers are organisms that directly or indirectly modulate the availability of resources to other species, by causing physical state changes in biotic or abiotic materials."

As one would expect, ecosystem engineering is the central concept of this paper. The organism type property is present in the abstract, and its dimensions are autogenic or allogenic. Properties such as spatial extent, persistence and resource flow modulation further describe this central concept. Spatial extent varies from local to regional, while persistence varies dimensionally from short to long. Resource flow modulation can be gaged in terms of number of flows and degree of control.

The extended phenotype concept appears in the abstract. However, the authors do not expand upon it in the opening paragraphs, and no properties are apparent.

The organism interactions concept also is present in the early part of this paper. It is associated with the usual properties of competition, predation, parasitism and mutualism. I will not provide further documentation since the paper largely ignores these traditional interactions after this point, preferring to focus on the unifying topic of ecosystem engineering.

Potential Concepts: ecosystem engineering (P: organism type D: autogenic or allogenic; P: spatial extent D: local to regional; P: persistence D: short to long; P: resource flow modulation D: number of flow, degree of control), extended phenotype, organism interactions

Text Segment	p. 377	Type	Memo

"Fig. 1. Conceptual models of autogenic and allogenic engineering by organisms."

The five ecosystem engineering cases provide a means of identifying and classifying organisms. Importantly, the first case illustrates what an ecosystem engineer is not. These cases and some of the surrounding discussion provoke a question. Do particular cases cause more severe or persistent environmental changes?

Classifying humanity's product and service systems according to this scheme might lead to some insights concerning environmentally acceptable practices, especially if mankind's system is compared with a natural example. Comparisons with natural systems could also suggest ways to execute environmental modifications that limit detrimental impact.

Text Segment	p. 380	Type	Memo

"The distinction between engineering that is subject to natural selection (because it is an extended phenotype) and engineering that is not ('accidental' engineering)…"

Here, one finds anther property for ecosystem engineering – <u>intention</u>. While biologists prefer to avoid teleology, it is clear that the difference between phenotypical and accidental engineering is intent. If evolution can select for a trait, then this trait benefits an organism's fitness. Intention's dimensions are binary. Ecosystem engineering is either an extended phenotype or accidental.

Potential Concepts: ecosystem engineering (P: organism type D: autogenic or allogenic; P: spatial extent D: local to regional; P: persistence D: short to long; P: resource flow modulation D: number of flow, degree of control; P: intention D: phenotype or accidental), extended phenotype, organism interactions

Text Segment	p. 381	Type	Memo

"…with a growing debate in ecology about the relative importance of such 'bottom up' vs 'top down' effects."

The organism interactions concept gains a new property late in this paper. The authors begin discussing the idea of control. They introduce 'bottom up' and 'top down' as types of control, examples of this dimension of control. They also introduce the idea of symmetry. Now, symmetry could be an independent property…ecological engineering symmetry…hmm… No, it fits best as a dimension of control. Control varies from symmetric to asymmetric.

Potential Concepts: ecosystem engineering (P: organism type D: autogenic or allogenic; P: spatial extent D: local to regional; P: persistence D: short to long; P: resource flow modulation D: number of flow, degree of control; P: intention D: phenotype or accidental; P: control D: type, asymmetric to symmetric), extended phenotype, organism interactions

Table 106: Summary of potential concepts, properties and dimensions for Jones 1994

Concepts	Properties	Dimensions
Ecosystem engineering	Organism type	Autogenic
		Allogenic
	Persistence	Short to long
	Resource flow modulation	Number of flows
		Degree of control
	Intention	Phenotype or accidental
	Control	Type (top down or bottom up)
		Asymmetric or symmetric
Extended phenotype	?	?
Organism interactions	?	?

Coder	John Reap	Date	7/7/2007
Text Segment	Paragraphs: all	Type	Memo
Reference	Jorgensen, Sven Erik (2002) "Explanation of ecological rules and observation by application of ecosystem theory and ecological models". *Ecological Modeling* 148: 241-248.		

"…rules are in all four cases in accordance with the principle that an ecosystem strives toward highest possible exergy..."

As an important concept, exergy maximization has been discussed in ecology for decades. The properties associated with exergy maximization include: thermodynamic gradients, through-flow and storage. These properties vary dimensionally from low to high. But, based on the author's comments, it would seem that a system maximizing exergy would need to have a high level of all three.

The author's objective in this article is to demonstrate that four common ecological observations can be explained by appealing to the exergy maximization concept. The first and most interesting three are listed in Table 107.

Rule	Trade-off
Lower mammal mortality leads to longer weaning periods	"…trade off is between slowing down the whole process of development to produce higher quality young, and dying during the period of investment…"
Lower mortality leads to later first births	"…trade off between delaying reproduction to a time when reproductive efficiency is high and dying while waiting."
"Exploitative competition can be explained by a slightly higher ratio growth rate / mortality"	NA

Table 107: Ecological rules explained by appealing to the exergy max. principle

He proves his contention by observing that each observation leads to higher levels of "stored" exergy. In other words, the rules maximize exergy by leading populations into configurations with high values for the property storage. Nothing is said about the other two properties.

Potential Concepts: exergy maximization (P: thermodynamic gradients D: low to high; P: through-put D: low to high; P: storage D: low to high)

Table 108: Summary of potential concepts, properties and dimensions for Jorgensen 2002

Concepts	Properties	Dimensions
Exergy maximization	Thermodynamic gradients	Low to high
	Through-put	Low to high
	Storage	Low to high

Coder	John Reap	Date	7/27/2007
Text Segment	Paragraphs: 1-12	Type	Memo
Reference	Kahmen, A., J. Perner and N. Buchmann (2005) "Diversity-dependent productivity in semi-natural grasslands following climate perturbations." *Functional Ecology* 19: 594-601.		

"According to the so-called 'insurance hypothesis', species diversity influences the stability or resistance of ecosystem functions against environmental perturbations."

Three main concepts appear in the early paragraphs: biodiversity, ecosystem and insurance hypothesis. The ecosystem property of interest in this article is stability; the authors are interested in the relationship between ecosystem stability and biodiversity's magnitude. As in other studies, stability varies from low to high, but biodiversity's magnitude is measured in terms of exponential Shannon-Wiener Index (effective diversity). They seem to subscribe to the biodiversity-ecosystem relationship known as the sampling hypothesis. This hypothesis states that increasing biodiversity increases stability by increasing the likelihood that a species in an area is adapted to withstand one or more environmental perturbations.

Potential Concepts: ecosystem (P: stability D: low to high), biodiversity (P: magnitude D: exponential Shannon-Wiener Index), sampling hypothesis

Text Segment	Paragraphs: 13-21	Type	Memo

"Our results are consistent with previous studies that have determined the importance of species composition for the stability of ecosystem functions."

As stated, the remainder of the paper largely shows that increasing the magnitude of biodiversity increases ecosystem stability. The authors also call attention to another potentially important property of ecosystems – evenness. Evenness seems to refer to species distribution; if so, it would be appropriate to dimension ecosystems as varying from well-mixed to patchy.

Potential Concepts: ecosystem (P: stability D: low to high; P: evenness D: well-mixed to patchy), biodiversity (P: magnitude D: exponential Shannon-Wiener Index), sampling hypothesis

Table 109: Summary of potential concepts, properties and dimensions for Kahmen 2005

Concepts	Properties	Dimensions
Ecosystem	Stability	Low to high
	Evenness	Well-mixed to patchy
Biodiversity	Magnitude	Exponential Shannon-Wiener Index
Sampling hypothesis	?	?

Coder	John Reap	Date	7/23/2007
Text Segment	Paragraphs: abstract - end	Type	Memo
Reference	Kiessling, W. (2005) "Long-term relationships between ecological stability and biodiversity in Phanerozoic reefs." *Nature* 433: 410-413.		

"Here I show that in biogenic reefs, ecological stability is related to taxonomic diversity on million-year timescales."

Kiessling's article deals with the relationship between biodiversity and ecosystems. Specifically, it relates the biodiversity's magnitude property to the stability property for ecosystems. When magnitude, which varies dimensionally by taxonomic diversity, is large, the author finds that stability, which varies from low to high, is high.

Later in the article, the author also discusses the ecosystem property of productivity which varies from low to high. He does not find a strong relationship between the magnitude of biodiversity and productivity.

Scale factors prominently in this article. The temporal and spatial scales covered by this study are incredible. He considers global coral diversity for more than 500 million years. As he correctly observes, this large scale study lends significant support to relationships revealed by experiments and models using smaller time and space scales.

Potential Concepts: biodiversity (P: magnitude D: taxonomic diversity), ecosystem (P: stability D: low to high; P: productivity D: low to high), scale

Table 110: Summary of potential concepts, properties and dimensions for Kiessling 2005

Concepts	Properties	Dimensions
Biodiversity	Magnitude	Species number
Ecosystem	Stability	Low to high
Scale	?	?

Coder	John Reap	Date	6/23/2007
Text Segment	Abstract – para. 2	Type	Memo
Reference	Kirwan, L. *et al*. (2007) "Evenness drives consistent diversity effects in intensive grassland systems across 28 European sites" *Journal of Ecology* 95: 530-539.		

"…increased crop diversity in species-poor intensive systems may improve their provision of ecosystem services."

This article centers upon the concepts of <u>diversity</u> and <u>ecosystem service</u>. Specifically, the authors attempt to relate the former to the later by comparing mixed crop plantings with monocultures grown at different locations throughout Europe. Diversity seems to have the property of <u>magnitude</u> which varies dimensionally by <u>species number</u> and <u>relative abundance</u>. In terms of ecosystem services they focus on biomass production and crop yields, though resistance to invasion is briefly noted. So, in this paper, the ecosystem service concept seems to the properties of <u>magnitude</u> and <u>stability</u> with magnitude dimensioned by <u>biomass production</u> and <u>yield</u> and stability dimensioned by <u>degree of invasion resistance</u>.

Summarizing their findings, it appears that high diversity, as measured by species number and relative abundance, leads to increased yields and biomass production while also displaying a high degree of ecosystem stability.

Potential Concepts: diversity (P: magnitude D: species number, relative abundance), ecosystem service (P: magnitude D: biomass production, yield; P: stability D: degree of invasion resistance)

Table 111: Summary of potential concepts, properties and dimensions for Kirwan 2007

Concepts	Properties	Dimensions
Diversity	Magnitude	Species number
		Relative abundance
Ecosystem service	Magnitude	Biomass production
		Yield
	Stability	Degree of invasion resistance

Coder	John Reap	Date	4/1/2007
Text Segment	Abstract – para. 2	Type	Memo
Reference	Kitano, Hiroaki (2004) "Biological Robustness" *????* 5: 826-837.		

"Robustness…is considered…a fundamental feature of complex evolvable systems."

A number of potential concepts appear in the abstract. The author begins with robustness and quickly relates it to evolvable systems. As presented, robustness is practically a property of evolvable systems, and the author makes such a claim in the first paragraph. His use of the term, "evolvable system," reminds me of the idea of open systems discussed in ME 6102. If the similarity is as close as I believe, then robustness and evolvable systems have a number of properties and dimensions – far too many to neatly consign robustness to the role of a simple property.

He also introduces concepts such as fragility and therapy; in the introductory two paragraphs he adds performance setback and perturbation. Fragility and performance setbacks also seem to be properties of evolvable systems. Evolution casts a long shadow in biology, touching most every aspect of the science of life. This is very likely the reason why many terms and concepts can seem and, indeed, might be subordinate to evolution. Therapy and perturbation seem more readily separable as concepts independent from evolution. Perturbation has the properties of internal and environmental, and they seem to vary dimensionally by type. For example, the author seems to suggest that most internal perturbations are genetic while one could imagine environmental perturbations being droughts, fires, diseases, etc.

Potential Concepts: evolvable system (P: robustness? D: ?; P: fragility? D: ?; P: performance setback D: ?), therapy, perturbation (P: internal D: by type, i.e. genetic; P: environmental D: by type, i.e. drought, disease)

Text Segment	Paragraphs: 3-9	Type	Memo

"…from the level of gene transcription to the level of systemic homeostasis…"

Not surprisingly, <u>scale</u> emerges during the discussion of robustness. The scale mentioned by the author is <u>spatial</u>, and it varies from that of <u>DNA to organisms</u>.

The author discusses state spaces and attractors. Perturbation response might be a property of robustness. It could vary dimensionally among <u>return to point attractor</u>, <u>return to periodic attractor</u>, <u>transition to new attractor</u> and <u>instability</u>. It is likely that my view is too literal.

He introduces the idea of <u>co-opted robustness</u> to describe a situation in which the robustness of a system perpetuates a detrimental system behavior.

The concept of <u>function maintenance</u> is used to clarify the purpose of robustness, and in this article it would be safe to use it as a synonym for robustness. Robustness is portrayed as a strategy for maintaining function in the face of internal and external perturbations. Interestingly, the engineering design community holds a similar view. Perhaps, quantifications of robustness could be based on the work already developed by Taguchi and the SRL.

Potential Concepts: scale (P: spatial D: DNA to organisms), robustness (P: perturbation response D: return to point attractor, periodic attractor, new attractor or instability), co-opted robustness, function maintenance.

Text Segment	Paragraphs: 10-13	Type	Memo

"System control consists of negative and positive feedback to attain a robust dynamic response…"

Feedback is presented as a means of achieving robustness in biological networks. It possesses the properties of positive, negative and integral. Positive and negative feedbacks are the bread and butter of control theory, but integral feedback is not familiar to me. The context in which it is presented does not elucidate its meaning.

Potential Concepts: feedback (P: positive D: ?; P: negative D: ?; P: integral D: ?)

Text Segment	Paragraphs: 14-19	Type	Memo

"Robustness can be enhanced if there are multiple means to achieve a specific function…"

In these paragraphs, the author introduces his alternative mechanism concept. Redundancy, overlapping functionality and diversity are described as different types of alternative mechanism. This makes them dimensions of the property type. Within this context, evolutionary capacitors, phenotypic plasticity and convergent evolution are also mentioned. The meaning of the term evolutionary capacitor is opaque. I would do well to review the references associated with this term. It seems that some argue that phenotypic plasticity is the antithesis of robustness, but this believes the opposite. Convergent evolution refers to the development of topologically similar gene networks.

Potential Concepts: alternative mechanism (P: type D: redundancy, overlapping functionality, diversity), evolutionary capacitors, phenotypic plasticity, convergent evolution

Text Segment	Paragraphs: 20-27	Type	Memo

"Modules are widely observed in various organisms, functioning as a possible biological design principle." "Decoupling isolates low-level variation from high-level functionalities."

The concepts of <u>modularity</u> and <u>decoupling</u> are related robustness strategies. Modularity appears to be a form of decoupling; the author believes that modules isolate the system from small scale failures. It is given the properties of <u>physical</u>, <u>functional</u>, <u>spatial</u> and <u>temporal</u>.

Decoupling's contribution to robustness lacks clear definition. The author mentions buffers, feedbacks and the damping of fluctuations. It might simply mean any mechanism that prevents the passage of fluctuations to a larger level. This is an idea worth revisiting.

Potential Concepts: modularity (P: physical D: ?; P: functional D: ?; P: spatial D: ?; P: temporal D: ?), decoupling

Text Segment	Paragraphs: 28-44	Type	Memo

"…there are architectural requirements for complex systems to be evolvable, which essentially requires the system to be robust…"

These paragraphs attempt to describe a general architecture for robust biological systems and elucidate the reasons for these architectures. Many previously mentioned concepts reappear. Decoupling reappears as buffering, for example, and the author discusses robust modules. The bow-tie structure concept is introduced. It has three properties: conserved core processes, conserved versatile interfaces and diverse inputs and outputs. It is not clear how these processes vary dimensionally. Metabolism, cell cycle and transcriptional machinery are listed as conserved core processes. The idea of "weak linkage" appears multiple times. As used, it relates to the conserved versatile interface.

Potential Concepts: bow-tie structure (P: conserved core processes D: ?; P: conserved versatile interfaces D: ?; P: diverse inputs and outputs D: ?)

Text Segment	Paragraphs: 45-50	Type	Memo

"…introduction of various control feedback loops generates trade-offs by causing instability when unexpected perturbations are encountered…"

These latter paragraphs focus on the previously mentioned property of fragility. The author contends that increasing the number of regulatory feedback loops leads to both greater robustness and, paradoxically, fragility. Fragility changes character, however. It varies dimensionally between general and specific with specific fragility beginning to dominate as a system becomes robust. The magnitude of the potential failure also changes. While becoming more specific, it grows in seriousness from serious to catastrophic. He also notes that increasing robustness tends to cause decreasing performance and higher resource demands. This contention would seem to make performance and resource demand properties of evolvable systems that vary dimensionally between high and low.

Potential Concepts: evolvable system (P: robustness? D:?; P: fragility D: general to specific; P: performance setback D: low to high; P: resource demand D: low to high)

Table 112: Summary of potential concepts, properties and dimensions for Kitano 2004

Concepts	Properties	Dimensions
Evolvable system	Robustness	?
	Fragility	General to specific
		Serious to catastrophic
	Performance setback	Low to high
	Resource demand	Low to high
Therapy	?	?
Perturbation	Internal	By type, i.e. genetic
	Environmental	By type, i.e. drought, disease
Scale	Spatial	DNA to organism
Robustness	Perturbation Response	Return to point attractor, periodic attractor, new attractor or instability
Co-opted robustness	?	?
Function maintenance	?	?
Feedback	Positive	?
	Negative	?
	Integral	?
Alternative mechanism	Type	Redundancy, overlapping functionality, diversity
Evolutionary capacitors	?	?
Phenotypic plasticity	?	?
Convergent evolution	?	?
Modularity	Physical	?
	Functional	?
	Spatial	?
	Temporal	?
Decoupling	?	?
Bow-tie structure	Conserved core processes	?
	Conserved versatile interfaces	?
	Diverse inputs / outputs	?

Coder	John Reap	Date	7/23/2007
Text Segment	Paragraphs: abstract	Type	Memo
Reference	Knight, T.M., M.W. McCoy, J.M. Chase, K.A. McCoy and R.D. Holt (2005) "Trophic cascades across ecosystems." *Nature* 437: 880-883.		

"…strong species interactions can reverberate across ecosystems..."

Concepts such as organism interaction, community dynamics, trophic cascade and food web are present in the abstract. Organism interaction properties include type and magnitude. Predation and mutualism are the two types of interactions discussed, and magnitude varies dimensionally from low to high. Trophic cascades appear to be changes in material and energy flows that ripple across food webs changing the flows to potentially distantly connected organisms. Magnitude seems to be one property of a trophic cascade that varies from low to high. The time series behavior would also seem to be of interest, but it is not mentioned in this article.

The thrust of this article is that a high degree of predation can lead to a high magnitude trophic cascade which in turn affects community dynamics in coupled food webs. The authors' specific example is one of fish that eat dragon fly larva which reduce the numbers of dragon flies near ponds. With fewer dragon flies, more bees can pollinate plants near the pond, increasing their reproductive rate.

Potential Concepts: organism interactions (P: type D: predation or mutualism; P: magnitude D: low to high), community dynamics, trophic cascade (P: magnitude D: low to high), food web

Table 113: Summary of potential concepts, properties and dimensions for Kitano 2005

Concepts	Properties	Dimensions
Organism interactions	Type	Predation, mutualism
		Species composition
	Magnitude	Low to high
Community dynamics	?	?
Trophic cascade	Magnitude	Low to high
Food web	?	?

Coder	John Reap	Date	4/31/2007
Text Segment	Chapter 2: p. 22-31	Type	Memo
Reference	Kormondy, E. (1976). Concepts of Ecology. Englewood, Prentice-Hall, Inc.		

"…efficiency of energy capture in gross production under natural conditions is seldom more than 3 per cent..."

Energy's flow through ecosystems is the main focus for the coded sections and most of the chapter. Concepts such as energy capture, assimilation, respiration loss and net production dominate the discussion. Energy capture, assimilation and net production share the property of efficiency which can be thought of as varying dimensionally from high to low. The idea of energy transfer appears when one considers the passage of energy from autotrophs to herbivores to carnivores. Available energy decreases as one climbs the ladder of predation from autotrophe to herbivore to carnivore. Efficiency, magnitude and destination are the properties of energy transfer. Efficiency and magnitude vary from low to high while destination varies by number and type.

To my mind, it is also worth noting the values for some of these efficiencies. Autotrophic energy capture varies between 1 and 3% while assimilation efficiencies (conversion of captured energy into useful energy) of 76% have been observed.

Potential Concepts: energy capture (P: efficiency D: low to high), assimilation ((P: efficiency D: low to high), respiration loss, net production (P: efficiency D: low to high), energy transfer (P: efficiency D: low to high; P: magnitude D: low to high; P: destination D: number, D: type)

Table 114: Summary of potential concepts, properties and dimensions for Kormondy 1976

Concepts	Properties	Dimensions
Energy capture	Efficiency	Low to high
Assimilation	Efficiency	Low to high
Respiration loss	?	?
Net production	Efficiency	Low to high
Energy transfer	Efficiency	Low to high
	Magnitude	Low to high
	Destination	Number
		Type

Coder	John Reap	Date	7/1/2007
Text Segment	Paragraphs: abstract - 5	Type	Memo
Reference	Laland, K.N., F.J. Odling-Smee and M.W. Feldman (1999) "Evolutionary consequences of niche construction and their implications for ecology" *Proceedings of the National Academy of Sciences* 96 (18): 10242-10247.		

"There is increasing recognition that all organisms modify their environments, a process that we call 'niche construction' but is elsewhere described as ecosystem engineering."

A focus on construction and interrogation of a simplified model for the evolutionary influences of niche construction reduces the number of concepts available in this article. One does learn that niche construction is synonymous with ecosystem engineering. The authors further specify the dimensions for this concept's type property. In hastings.memo, I used the term allogenic to describe modifications to the physical environment. This dimension can be subdivided into allogenic artifacts and allogenic habitat modifications.

Biology's big concepts such as selection and evolution pervade this work. Interestingly, momentum appears to be a property of evolution, which presumably varies between low and high. Quantifying evolutionary momentum seems difficult, though.

Potential Concepts: ecosystem engineer (P: type D: autogenic, allogenic artifacts, allogenic habitat modifications), selection, evolution (P: momentum D: low and high)

Text Segment	Paragraph: 24	Type	Memo

"…a major ecological consequence of the niche construction of organisms is that it establishes 'engineering webs,' or control webs, in…ecosystems."

This control web concept deserves exploration. Apparently, control webs operate in ways altogether different from food webs or trophic relations. If ecosystem engineers are as common as the last few papers suggest, their control webs must be equally common and might hold insights entirely separate from the ones encountered thus far.

Potential Concepts: ecosystem engineer (P: type D: autogenic, allogenic artifacts, allogenic habitat modifications), selection, evolution (P: momentum D: low and high), control web

Table 115: Summary of potential concepts, properties and dimensions for Laland 1999

Concepts	Properties	Dimensions
Ecosystem engineer	Type	Autogenic, allogenic artifacts, allogenic habitat modifications
Selection	?	?
Evolution	Momentum	Low to high
Control web	?	?

Coder	John Reap	Date	7/8/2007
Text Segment	Paragraphs: abstract-1	Type	Memo
Reference	Lange, Marc (2005) "Ecological laws: what would they be and why would they matter?" *Oikos* 110 (2): 394-403.		

"I argue that ecological laws would have to possess collectively a distinctive kind of invariance under counterfactual perturbations."

Two distinct kinds of concepts exist in this opinion paper. One set presents the author's ideas about identifying and confirming scientific laws for ecology; the other applies to examples of potential laws that he uses to illustrate his method. Ecological law, in fact, is a concept fitting into the first category. In the author's mind, it possesses the property of counterfactual invariance. Counterfactual invariance is maintained when counterfactual suppositions fail to reduce the predictive capacity of the law or are ruled irrelevant. I think.

Potential Concepts: ecological law (P: counterfactual invariance D: ?)

Text Segment	Paragraphs: 2-18	Type	Memo

"Laws of ecology – like the laws of thermodynamics – would be 'substrate neutral' and hence applicable even to certain hypothetical systems that violate the fundamental laws of physics."

Substrate neutrality is another property of an ecological law assigned by the author. The presence of this property suggests that ecological laws trace their causality to phenomena of a greater scale than that dictated by some physical laws. Later in the text, the author introduces the cute example of birds made of some other substance besides atoms that, nonetheless, still behave like birds. He argues that ecological laws would still apply, despite the violation of atomic scale laws. A lack of dimensions presents a problem for measuring these properties, which in turn presents a problem for making his concept operational.

Necessity is also stated as a property of an ecological law.

Potential Concepts: ecological law (P: counterfactual invariance D: ?; P: substrate neutrality D:?: P: necessity D:?)

Text Segment	Paragraphs: 21	Type	Memo

"…to be stable for a given field's purposes, the set's members must all be invariant under every counterfactual supposition that is relevant to the field and consistent with every member of the set."

This paragraph introduces the consistency property for ecological laws. This property helps eliminate irrelevant counterfactual suppositions.

Potential Concepts: ecological law (P: counterfactual invariance D: ?; P: substrate neutrality D:?: P: necessity D:?; P: consistency D:?)

Text Segment	Paragraphs: 22-39	Type	Memo

"…'area law': that the number S of species of a given taxonomic group on an 'island'…in a give 'archipelago' increases, ceteris paribus, with the island's area A in accordance with a power function ($S=cA^z$)."

While continuing to discuss his power law concept, the author introduces two examples that worthy of concepts. The area law and longitudinal species proportionality law are the two examples used by the author to illustrate his ecological law concept. As the quote reveals, the area law states that species number is proportional to land area. The longitudinal law states that the number of species increases as one moves from the poles toward the equator. Properties and dimensions for these concepts are not evident in this paper. I will need to look elsewhere to expand these ideas.

Potential Concepts: ecological law (P: counterfactual invariance D: ?; P: substrate neutrality D:?: P: necessity D:?; P: consistency D:?), area law, longitudinal species proportionality law

Table 116: Summary of potential concepts, properties and dimensions for Lange 2005

Concepts	Properties	Dimensions
Ecological law	Counterfactual invariance	?
	Substrate neutrality	?
	Necessity	?
	Consistency	?
Area law	?	?
Longitudinal species proportionality law	?	?

Coder	John Reap	Date	7/1/2007
Text Segment	Paragraphs: abstract - 20	Type	Memo
Reference	Leibold, M.A., M. Holyoak, N. Mouquet, P. Amarasekare, J.M. Chase, M.F. Hoopes, R.D. Holt, J.B. Shurin, R. Law, D. Tilman, M. Loreau and A. Gonzalez (2004) "The metacommunity concept: a framework for multi-scale community ecology" *Ecology Letters* 7: 601-613.		

"We then identify four paradigms for metacommunities: the patch-dynamic view, the species sorting view, the mass effects view and the neutral view..."

Introduced concepts relate to metacommunities and four different qualitative models which claim to describe their operation. Size is one property of a metacommunity that varies dimensionally by number of interacting patches. Connectivity is, by definition, another property because communities (patches of interacting species) connect to each other by species dispersal. Dispersal pathways or number of links provide a dimension for connectivity.

The patch-dynamic view, species sorting view, mass effects view and neutral view are the other obvious concepts introduced by this paper. Each is a qualitative model meant to describe the functioning of a metacommunity. It is doubtful that coding these models in detail is of great value. It seems better to identify underlying concepts common to all four. A patch is one such concept. Each patch is, "A discrete area of habitat." Patches have the properties of size and abiotic features, which respectively vary from small to large and by type. Feedback lurks in the background when one discusses metacommunities and their models. Signal is one property of feedback that varies dimensionally by both type and strength.

Potential Concepts: metacommunities (P: size D: number of interacting patches; P: connectivity D: number of links), patch-dynamic view, species sorting view, mass effects view and neutral view, patch (P: size D: small to large; P: abiotic features D: type), feedback (P: signal D: type, strength)

Text Segment	p. 610	Type	Memo

On the final page, the author observes that diversity might cause different effects at different scales. It might destabilize "closed local communities" while promoting stability on a regional level.

Table 117: Summary of potential concepts, properties and dimensions for Leibold 2004

Concepts	Properties	Dimensions
Metacommunities	Size	Number of interacting patches
	Connectivity	Number of links
Patch	Size	Small to large
	Abiotic features	Type
Feedback	Signal	Type
		Strength
Patch-dynamic view	?	?
Species sorting view	?	?
Mass effects view	?	?
Neutral view	?	?
Diversity	?	?

Coder	John Reap	Date	1/25/2007
Text Segment	Paragraphs: 1-7	Type	Memo
Reference	Lotka, A.J. "Contribution to the Energetics of Evolution." *Proceedings of the National Academy of Sciences* 8: 147-151.		

"…the fundamental object of contention in the life-struggle…is available energy. …in the struggle for existence, the advantage must go to…organisms whose energy-capturing devices are most efficient at directing available energy into channels favorable to the preservation of the species."

The author's opening lines contain two concepts, life-struggle and available energy, that he discusses for the remainder of the paper. Life-struggle is almost certainly synonymous with evolution, though a case may be made for the concept of natural selection. Available energy seems to have the properties of availability and utilization. Both of these properties emerge when taking the perspective of the biosphere or "organic world," as Lotka labels it. Available energy's availability seems to have dimensions ranging from abundant to scarce while utilization ranges from full to unutilized.

He contemplates the relationship between natural selection and available energy and formulates a hypothesis about this relationship in the first few paragraphs. He hypothesizes that natural selection works to maximize "energy flux through the system" by preserving and increasing organisms that capture energy efficiently. This hypothesis introduces the concept of energy capture with the property of efficiency and dimensions between efficient and inefficient. So, using the concepts, properties and dimensions presented thus far, Lotka hypothesizes that natural selection in the presence of abundant available energy guides the biosphere toward higher utilization by selecting efficient energy capturing organisms.

Potential Concepts: evolution, natural selection, available energy (P: availability D: abundant to scarce; P: utilization D: full to unutilized), energy capture (P: efficiency D: efficient to inefficient)

Text Segment	Paragraphs: 8-17	Type	Memo
Reference	Lotka, A.J. "Contribution to the Energetics of Evolution." *Proceedings of the National Academy of Sciences* 8: 147-151.		

"This may be expressed by saying that natural selection tends to make the energy flux through the system a maximum, so far as compatible with the constraints to which the system is subject."

With this text segment, the concept of <u>constraint</u> enters his thinking. Earlier, he mentions mass as a type of constraint; so, <u>mass</u> might be a property. However, he argues that a lack of mass would not inhibit energy flux maximization; material turnover rates simply increase. In the final paragraph he returns to the idea of constraints. His clearly states that matter remains open, suggesting another property, though <u>other constraint</u> is not a particularly satisfying label for a property.

Potential Concepts: constraint (P: mass P: other constraint)

Table 118: Summary of potential concepts, properties and dimensions for Lotka

Concepts	Properties	Dimensions
Evolution		
Natural selection		
Available Energy	Availability	Abundant to Scarce
	Utilization	Full to Unutilized
Energy Capture	Efficiency	Efficient to Inefficient
Constraint	Mass	
	Other Constraint	

Coder	John Reap	Date	7/15/2007
Text Segment	Paragraphs: abstract - end	Type	Memo
Reference	Maherali, Hafiz and John N. Klironomos (2007) "Influence of Phylogeny on Fungal Community Assembly and Ecosystem Functioning." *Science* 316: 1746-1748.		

"…findings suggest that phylogenetic trait conservatism can promote coexistence because of reduced competition between distinct evolutionary lineages and enhance ecosystem function because of functional complementarity among those same lineages."

The primary concepts in this article are ecosystem, diversity and organism interactions. Ecosystems have the property of productivity which can vary dimensionally from low to high. Two kinds of or properties for diversity occur in the article – taxonomic and functional. Taxonomic diversity varies by species number while functional diversity varies by number of functions. Organism interactions are defined by the properties type and magnitude. Type includes competition and complementarity.

Using these concepts, properties and dimensions, one restates the authors' conclusions as follows. Ecosystem productivity is high when functionally diverse species interact in a complementary ways. Taxonomic diversity is not as important as functional diversity.

Potential Concepts: ecosystem (P: productivity D: low to high), diversity (P: taxonomic D: species number; P: functional D: number of functions), organism interactions (P: type D: competition, complementarity; P: magnitude D: low to high)

Table 119: Summary of potential concepts, properties and dimensions for Maherali 2007

Concepts	Properties	Dimensions
Ecosystem	Productivity	Low to high
Diversity	Taxonomic	Species number
	Functional	Number of functions
Organism interactions	Type	Competition, complementarity
	Magnitude	Low to high

Coder	John Reap	Date	1/26/2007
Text Segment	Paragraphs: abstract - 2	Type	Memo
Reference	Makarieva, A.M., V.G. Gorshkov and B-L. Li. (2005) "Energetics of the smallest: do bacteria breathe at the same rate as whales?" *Proceedings of the Royal Society B* 272: 2219-2224.		

In the abstract, the author's present their focal concept of metabolic rate. The fact that the abstract is dominated by statements about different kinds of metabolic rates and the metabolic rates of various organisms indicates this concept's central importance. Metabolic rate seems to have many properties. It can be mass-specific, tissue-specific, growing, basal and energy-saving. Properties such as mass-specific and basal seem to vary continuously by numerical value; their dimensions range from high to low. The others seem to vary discretely. Tissue specific would seem to vary dimensionally by tissue type: nerve, muscle, bone. Energy-saving would vary by type of regime: hibernating, sit-and-wait, anoxia, etc. Growth might be considered to vary discretely; one could think in terms of type (i.e. reproduction or maturation). Or, one might think of it in terms of material addition – fast to slow.

Ecological dominance and universal limits also might be concepts. However, the former is introduced to underscore the importance of learning about bacterial metabolic rates.

Potential Concepts: metabolic rate (P: mass-specific D: high to low; P: basal D: high to low; P: tissue-specific D: tissue type; P: energy-saving D: regime type; P: growing D: type, D: fast to slow), ecological dominance, universal limits

Text Segment	Paragraphs: 11-16	Type	Memo

"…mass-specific metabolic rates of living cells vary within universal limits…independent of the size of the organism…"

The above quoted excerpt summarizes the authors' findings and highlights the importance of the universal limits concept introduced in the abstract. The authors repeatedly discuss the concept of a universal limit on living cells with regard to specific metabolic rates. They compare and contrast power law estimates with specific metabolic rates, note the similarity between mean mammal, insect and arthropod specific metabolic rates and conclude with statements about the uniformity of "energy supply per unit mass." So, the specific metabolic rate appears to be a property of universal limits. The dimensions of mass specific metabolic rate would seem to be the same as those for metabolic rate's mass specific property, namely high to low.

In the closing paragraph, the concept of ecological dominance reappears, and the concept of natural selection makes its first appearance in this paper. The authors connect these two concepts with the paper's central concepts, metabolic rates and universal limits. They suggest that natural selection may favor particular rates or ranges and that these favored rates may be associated with ecological dominance.

Potential Concepts: universal limits (P: specific metabolic rate D: high to low), natural selection

Table 120: Summary of potential concepts, properties and dimensions for Makarieva 2005

Concepts	Properties	Dimensions
Metabolic Rate	Mass-specific	High to low
	Basal	High to low
	Tissue-specific	Tissue type
	Energy-saving	Regime type (i.e. hibernating)
	Growing	Type (reproduction vs. maturation)
		High to low rate
Ecological dominance		
Universal Limits	Specific Metabolic Rate	High to Low
Natural Selection		

Coder	John Reap	Date	7/10/2007
Text Segment	Paragraphs: abstract – p. 1750	Type	Memo
Reference	Marquet, P.A., R.A. Quinones, S. Abades, F. Labra, M. Tognelli, M. Arim and M. Rivadeneira (2005) "Scaling and power-laws in ecological systems" *Journal of Experimental Biology* 208: 1749-1769.		

"…the analysis of power-law and scaling relationships can help us to identify general principles that apply across a wide range of scales and levels of organizations, revealing the existence of universal principles...."

This passage summarizes my interest in this paper. I hoped to find statements of these "universal principles" or sufficient numbers of related concepts to allow formulation of them. What I found was something different and less satisfying.

Power law relationships appear in other articles, but these authors introduce their mathematical properties of scale-invariance and universality. Scale invariance simply means that a power law's functional form remains constant despite changes in spatial or temporal scale. A different multiplicative factor is used to account for differences. Universality is a mathematical phenomenon that seems to occur in many types of dissimilar systems near critical points. Near these critical points, system behavior can be modeled with power laws that share common exponents.

<u>Universality</u> is also a good word for the concept with which the authors grapple. They want to find a unifying set of power relations that can explain observed behaviors in ecology that are unaffected by geography, life history or period of time. In fact universality has the property of <u>invariance</u>; a universal power relation would possess a high degree of invariance in the face of external influences.

Potential Concepts: univerality (P: invariance D: low to high)

Text Segment	p. 1752	Type	Memo

"…to calculate how much space or area would an individual require or its home range (H)…."

Home range is a potentially useful concept introduced on this page. The authors formulate a body mass based scaling law for home ranges of an organism that is based on metabolism and resource availability. The properties of this home range include size and resource density which vary dimensionally from low to high. The presented power relation calculates the minimum size for homogeneous resource distribution.

Potential Concepts: univerality (P: invariance D: low to high), home range (P: size D: low to high; P: resource density D: low to high)

Text Segment	p. 1754-1755	Type	Memo

"…one of the most intriguing consequences of biological scaling laws is the emergence of invariant quantities."

The invariants concept is of interest because two identified invariant relationships are of interest. Labeled the "energetic equivalence rule" and the "linear biomass hypothesis," they are examples of scale invariant relationships that do not change with body mass (M^0). The first combines two power relationships with opposite exponents to reveal that energy consumption per unit area is roughly the same for different species. The second states that total biomass decreases linearly as size class increases.

While I do not see much to code on these pages, these two relations in conjunction with the specific metabolic rate limit presented in other articles may suggest limits for human activities.

Potential Concepts: univerality (P: invariance D: low to high), home range (P: size D: low to high; P: resource density D: low to high), invariants

Text Segment	p. 1756	Type	Memo

Two other noteworthy concepts appear in this paper. The ecosystem concept is presented with the property of <u>structure</u> in conjunction with the dimension of <u>biomass spectra</u>. The <u>zero-sum dynamics</u> concept is another interesting idea that is not well described in this paper.

Potential Concepts: univerality (P: invariance D: low to high), home range (P: size D: low to high; P: resource density D: low to high), invariants, ecosystem (P: structure D: biomass spectra), zero-sum dynamics

Table 121: Summary of potential concepts, properties and dimensions for Marquet 2005

Concepts	Properties	Dimensions
Universality	Invariance	Low to high
Home range	Size	Low to high
	Resource density	Low to high
Invariants	?	?
Ecosystem	Structure	Biomass spectra
Zero-sum dynamics	?	?

Coder	John Reap	Date	6/23/2007
Text Segment	Paragraphs: 1-?	Type	Memo
Reference	Maxwell, K.L. and L. Frappier (2007) "Viral Proteomics" *Microbiology and Molecular Biology Reviews* 71 (2): 398-411.		

"…development of proteomic methods has revolutionized our ability to assess protein interactions and cellular changes…allowing the discovery of previously unknown connections."

Maxwell and Frappier devote the entire length of this article to descriptions of virus protein identification techniques, successes and failures. Clearly, <u>protein</u> is a concept of prime interest in this article. With the emphasis on identification techniques, it is also clear that <u>detection</u> is a property of proteins that varies dimensionally from <u>low to high</u> and by <u>method</u>.

I did not extract much else from this article beyond these basic ideas. I could code the terminology surrounding different detection techniques and objectives, but this hardly seems valuable.

Potential Concepts: protein (P: detection D: low to high, by method)

Table 122: Summary of potential concepts, properties and dimensions for Maxwell 2007

Concepts	Properties	Dimensions
Protein	Detection	Low to high
		By method

Coder	John Reap	Date	6/8/2007
Text Segment	Paragraphs: 1-7	Type	Memo
Reference	May, Robert M. (1972) "Will a Large Complex System be Stable" *Nature* 238: 413-414.		

"…large complex systems which are assembled (connected) at random may be expected to be stable up to a certain critical level of connectance..."

Networks are the underlying concept in this paper. The author discusses and quantifies properties related to network structure. He discusses properties such as size, interaction magnitude, connectance, and stability. All of these can vary dimensionally via node number or from low to high, but this paper's great value stems from the author's ability to quantify and relate these properties using reasonably straightforward mathematical forms. He sets network stability criteria based on average interaction "strength" or magnitude (a) and network size (n), stating that networks tend to be stable when

$$a<(n)^{-0.5}$$

and unstable when

$$a>(n)^{-0.5}$$

Defining connectance (C) as the ratio of actual links in a network to the possible number of links, he presents similar equations for stability and instability, respectively.

$$a<(Cn)^{-0.5}$$

$$a>(Cn)^{-0.5}$$

Potential Concepts: networks [or network structure] (P: size D: node number; P: interaction magnitude D: low to high; P: connectance D: low to high; P: stability D: low to high)

Text Segment	Paragraphs: 8-13	Type	Memo

His final paragraphs introduce two related concepts: network equivalence and modularity. He provides the equation $a_1^2C_1 \sim a_2^2C_2$ as a rough means of quantitatively comparing stability characteristics. He argues that systems with highly connected nodes do not have strong inter-node interactions, and conversely, systems with strong interactions have few inter-node connections. He then observes that modular arrangements are more stable.

Potential Concepts: networks [or network structure] (P: size D: node number; P: interaction magnitude D: low to high; P: connectance D: low to high; P: stability D: low to high), network equivalence, modularity

Table 123: Summary of potential concepts, properties and dimensions for May 1972

Concepts	Properties	Dimensions
Networks	Size	Node number
	Interaction	Low to high
	Connectance	Low to high
	Stability	Low to high
Network equivalence	?	?
Modularity	?	?

Coder	John Reap	Date	6/28/2007
Text Segment	Paragraphs: abstract - 14	Type	Memo
Reference	Mitchell, J.G. (2002) "The Energetics and Scaling of Search Strategies in Bacteria" *The American Naturalist* 160 (6): 727-740.		

"Here, the relationship between bacterial size and movement cost is established and shown to fit the same allometric equation as that for size and movement cost in animals."

Mitchell examines the energetics of bacterial mobility. Specifically, he generates quantitative estimates for forward motion and reorientation. Encountered concepts include: life-history strategy and motility. Motility possesses the properties of energy cost and strategy. Energy cost varies dimensionally from low to high. The author restates and generates equations that estimate the actual costs for various motility strategies. Some of these equations reveal minimum energy expenditures that correspond to particular configurations of bacterial body size and motility strategy. Strategy varies dimensionally by type (run and tumble, run and arc, migratory run and reverse and local run and reverse). It should be noted that the author only considers a particular subset of mobile single-celled organisms – bacteria with flagella know to execute the four stated strategies.

Potential Concepts: life-history strategy, motility (P: energy cost D: low to high; P: strategy D: Type)

Text Segment	Paragraphs: 22-24	Type	Memo

"…the slope survives the transition from turbulent to laminar flow across all Reynolds numbers at which organisms swim."

This passage and the author's statements about the broader implications of his findings hold significance for my work with specific metabolic limits. Yuri constructed an interesting power law that fit data ranging from insects to human powered aircraft. The size ranges involved in Yuri's fit are comparable to those used by Mitchell when plotting his data for swimming bacteria with that for fish. It would be interesting to see if these two plots were similar. Presumably, one could develop a similar set of allometric equations to estimate flight power consumption for birds and, potentially, aircraft.

Potential Concepts: life-history strategy, motility (P: energy cost D: low to high; P: strategy D: Type)

Table 124: Summary of potential concepts, properties and dimensions for Mitchell 2002

Concepts	Properties	Dimensions
Motility	Energy cost	Low to high
	Strategy	Type (run and tumble, run and arc, migratory run and reverse and local run and reverse)
Life-history strategy	?	?

Coder	John Reap	Date	7/19/2007
Text Segment	Paragraphs: abstract-8	Type	Memo
Reference	Montoya, J.M., S.L. Pimm and R.V. Sole (2006) "Ecological networks and their fragility." *Nature* 442: 259-264.		

"Ecological networks, although complex, have well defined pattern that both illuminate the ecological mechanisms underlying them and promise a better understanding of the relationship between complexity and ecological stability."

This article contains a veritable raft of concepts. Many are present in previously coded papers, though some receive clearer definitions in this treatment. The concepts of <u>organism interaction</u> and <u>ecological network</u> resurface in the abstract. Organism interactions have the property of <u>type</u> which varies from <u>predation</u> through <u>herbivory</u> to <u>mutualism</u>. Properties for ecological networks include: <u>stability</u>, <u>resilience</u>, <u>persistence</u> and <u>structure</u>.

Potential Concepts: organism interactions (P: type D: predation to mutualism), ecological network (P: stability D:?; P: resilience D:?; P: persistence D:?; P: structure D: ?)

Text Segment	Paragraphs: 8-end	Type	Memo

"…densely clustered webs are nearer the norm, not exceptions. Moreover, compartments are likely to correspond to habitat boundaries..."

As the article proceeds, the dimensional richness of the structure property for ecological networks increases. Structure can be measured in terms of <u>complexity</u>, <u>clustering</u>, <u>connectance</u>, <u>linkage strength</u> and <u>modularity</u>. The authors provide a succinct definition for each.

<u>Complexity (or linkage density)</u> – "average number of trophic links per species"

Connectance – "linkage density" divided by total number of species in the web

Linkage strength – magnitude of effects of one species upon another

Clustering – fraction of species with a direct link to a focal species

Modules or Compartments – Groups of species sharing strong linkages that are weakly linked to other species or groups

It is mentioned late in the paper that resilience varies dimensionally by eigenvalue. This is the second occurrence of eigenvalues in relation to ecosystem stability. It might be a powerful, quantitative way of comparing human and ecological networks.

It should also be noted that the authors believe consensus on ecosystem networks is lacking, and therefore, many of the statements about ecological structures remain hypotheses.

Potential Concepts: organism interactions (P: type D: predation to mutualism), ecological network (P: stability D:?; P: resilience D:?; P: persistence D:?; P: structure D: ?)

Table 125: Summary of potential concepts, properties and dimensions for Montoya 2006

Concepts	Properties	Dimensions
Ecological network	Stability	?
	Resilience	Eigenvalue
	Structure	Complexity
		Clustering
		Connectance
		Linkage strength
		Modularity
	Persistence	?
Organism interactions	Type	Predation to mutualism

Coder	John Reap	Date	7/15/2007
Text Segment	Paragraphs: abstract – p. 338	Type	Memo
Reference	Morris, S. Conway (1998) "The evolution of diversity in ancient ecosystems: a review" *Philosophical Transactions of the Royal Society of London B* 353: 327-345.		

"…some but perhaps not all mass extinctions are characterized by long lag-times of recovery, which may reflect the slowing waning of extrinsic forcing factors or alternatively the incoherence associated with biological reassembly of stable ecosystems."

Despite the promising title, this paper devotes most of its verbiage to potential inaccuracies in fossil records, core samples and the like. The ecosystem concept is present, and its properties of stability and resilience appear in the abstract and other points in the text. The assumed dimensions for both of these properties are noteworthy in that they are measures based on species diversity. Stability is assumed to vary dimensionally by number of species while resilience is measured as the rate of origination (opposite of extinction rate).

Of course, diversity is also a concept prominent in this work, but it is written about in the context of ecosystems. It might be argued that it is a property in this work.

Potential Concepts: ecosystem (P: stability D: number of species; P: resilience D: rate of origination), diversity

Text Segment	p. 339, paragraph 7	Type	Memo

"The fractal structure, it is suggested, could be consistent with self-organized criticality."

In the paper's conclusion, one finds provocative statements about a metric for diversity. Fractal structure seems to be a property of diversity, and it seems to vary from self-similar to dissimilar, though this idea bares further investigation. This might be a new or, at least, uncommon way of measuring diversity in ecosystems, and therefore, it might have some value in industrial ecology or related disciplines.

Potential Concepts: ecosystem (P: stability D: number of species; P: resilience D: rate of origination), diversity (P: fractal structure D: self-similar to dissimilar)

Table 126: Summary of potential concepts, properties and dimensions for Morris 1998

Concepts	Properties	Dimensions
Ecosystem	Stability	Number of species
	Resilience	Rate of origination
Diversity	Fractal structure	Self-similar to dissimilar

Coder	John Reap	Date	6/30/2007
Text Segment	Paragraphs: abstract - 6	Type	Memo
Reference	Moses, M.E. and J.H. Brown (2003) "Allometry of human fertility and energy use." *Ecology Letters* 6: 295-300.		

"Fertility declines as energy consumption increases with a scaling relationship of -1/3 as predicted by allometric theory."

The paper's three main concepts of fertility, metabolic requirements and energetic network constraints appear in the abstract. Statements about declines in fertility reveal that it has the property of magnitude which varies from low to high. Metabolic requirements also possess the property of magnitude which varies from low to high, but importantly, they are also distinguished by type which is either intrinsic or extrinsic. Humans are the only creatures with extrinsic metabolic requirements.

Energetic network constraints take the form of allometric scaling relations in the first few paragraphs. The authors begin to connect decreasing fertility to increasing metabolic requirements using allometric relations for energetic network constraints. It is important to note that energetic constraints are recognized in biology, but the existence of a "network" based explanation is largely the position taken by West and Brown.

Potential Concepts: fertility (P: magnitude D: low to high), metabolic requirements (P: magnitude D: low to high; P: type D: intrinsic to extrinsic) energetic network constraints

Text Segment	Paragraphs: 19-end	Type	Memo

"We suggest that I human societies, as in the bodies of organisms, larger networks deliver more energy, but with increased total transport time and infrastructure cost."

Properties such as <u>scaling</u> and <u>generality</u> add to one's understanding of energetic network constraints. Scaling varies dimensionally by <u>functional form</u>; the authors believe that these constraints scale according to a power law for energy – $E^{-1/3}$. Generality varies from <u>specific to universal</u>. In this case, an energetic power law applies for organisms, and the same relation may apply for energy dependent physical networks. The fact that this is one of the authors' hypotheses indicates their belief in the universality of this relation.

Summarizing the authors beliefs using the presented codes, one can state that fertility's decline in relation to an increase in extrinsic metabolic requirements is governed by a general energetic network constraint which takes the form of a power law.

Potential Concepts: fertility (P: magnitude D: low to high), metabolic requirements (P: magnitude D: low to high; P: type D: intrinsic to extrinsic) energetic network constraints (P: scaling D: functional form; P: generality D: specific to universal)

Table 127: Summary of potential concepts, properties and dimensions for Moses 2003

Concepts	Properties	Dimensions
Fertility	Magnitude	Low to high
Metabolic requirements	Magnitude	Low to high
	Type	Intrinsic or extrinsic
Energetic network constraint	Scaling	Functional form
	Generality	Specific to universal

Coder	John Reap	Date	7/11/2007
Text Segment	Paragraphs: 4-14	Type	Memo
Reference	Murray, Bertram G. Jr (2000) "Universal laws and predictive theory in ecology and evolution." *Oikos* 89(2): 403-408.		

"Genotypes and phenotypes with the greatest Malthusian parameter increase more rapidly than those with small Malthusian parameters."

Drawing from a number of sources, Murray advances five laws for biological science. The first three apply to evolution while the last two apply to population dynamics. The passage written above is the first of Murray's laws for evolution.

Biological concepts such as genotype, phenotype and Malthusian Parameter appear as in vivo codes in the passage. Related concepts such as fecundity and survival appear in the text surrounding the passage. Now, to the best of my knowledge, a phenotype is an observable or manifest trait while a genotype is the genetic code for a trait. The *Dictionary of Scientific and Technical Terms 5th Ed.* effectively defines these terms in that way. The definitions of genotype and phenotype suggest properties such as influence and source, respectively, but since these properties do not appear in the text, I will not consider them here. Manifestation variation is a property mentioned for genotype; apparently, genotype can produce different phenotypes in response to different environmental conditions.

Equations combining Malthusian parameter with genotype or phenotype are stated.

Potential Concepts: genotype (P: manifestation variation D: ?), phenotype, Malthusian parameter, fecundity, survival

Text Segment	Paragraphs: 15	Type	Memo

"In the absence of changes in selection forces, a population will reach and remain in an evolutionary steady state."

Two of the big ideas in biology, evolution and selection, are in the statement of Murray's "second law of evolution." In it, we learn that evolution can have a rate of change that varies dimensionally from zero (steady state) to high. Now, this is interesting. Can evolution occur at any rate, or does a limit exist?

After this, Murray discusses three more laws for evolution and population dynamics. He continues the development of the equations advanced for his first law. They deserve further consideration if population dynamics play a larger role in understanding sustainability.

Potential Concepts: genotype (P: manifestation variation D: ?), phenotype, Malthusian parameter, fecundity, survival, evolution (P: rate of change D: Zero to high), selection

Table 128: Summary of potential concepts, properties and dimensions for Murray 2000

Concepts	Properties	Dimensions
Genotype	Manifestation variation	?
Phenotype	?	?
Malthusian parameter	?	?
Fecundity	?	?
Survival	?	?
Evolution	Rate of change	Zero to high
Selection	?	?

Coder	John Reap	Date	7/23/2007
Text Segment	Paragraphs: all	Type	Memo
Reference	Naeem, S. and A.C. Baker (2005) "Paradise sustained." *Nature* 433: 370-371.		

"…biodiversity may indeed govern sustainability."

In this very short article, the authors discuss the relationship between the concepts of ecosystem and biodiversity. Ecosystems are assigned properties such as stability, function and persistence. Stability varies dimensionally from low to high. Magnitude is the only dimension for biodiversity discussed in the article, and it varies by species number (richness). Citing another study, the authors believe that ecosystem stability and persistence increase as species number increases. This is a common theme in ecology.

Potential Concepts: biodiversity (P: magnitude D: species richness), ecosystem (P: function D:?; P: stability D: low to high; P: persistence D:?)

Table 129: Summary of potential concepts, properties and dimensions for Naeem 2005

Concepts	Properties	Dimensions
Biodiversity	Magnitude	Species number
Ecosystem	Function	?
	Stability	Low to high
	Persistence	?

Coder	John Reap	Date	6/4/2007
Text Segment	Paragraphs: abstract to para. 4	Type	Memo
Reference	Neinhuis, C. and W. Barthlott (1997) "Characterization and Distribution of Water-repellent, Self-cleaning Plant Surfaces" *Annals of Botany* 79: 667-677.		

"…ultrastructure of epidermal surfaces has been investigated with respect to taxonomic, as well as functional aspects."

Epidermal microsurfaces serve as one of this article's primary concepts. They possess properties such as water-repellency, adhesion, roughness and waxiness. Water-repellency is quantitatively dimensioned by contact angle, which varies from low to high. Epidermal surfaces with high contact angles repel water well. Adhesion varies from low to high and by type of contaminant. Roughness is measured in terms of cell convexity; smooth surfaces show slight cell convexity while rough ones have distinctive cell convexity. Waxiness varies from thin to thick. According to the authors, distinctively convex cells that form thick, waxy epidermal surfaces have high contact angles for water and low adhesion for contaminants such as dust and pollen.

Potential Concepts: epidermal microsurfaces (P: water-repellency D: low to high contact angle; P: adhesion D: low to high, D: contaminant type; P: roughness D: slight to distinctive cell convexity; P: waxiness D: thin to thick)

Text Segment	Paragraphs: 4-10	Type	Memo

"…epidermal surfaces of water repellent leaves displayed several special features to increase roughness."

These paragraphs expand the meanings of properties such as water-repellency and roughness. One learns that roughness varies by type of geometry (convex, papillose and hairy) as well as degree of convexity. Papillose geometries are nipple-shaped structures. Water-repellency can be long to short in duration.

Potential Concepts: epidermal microsurfaces (P: water-repellency D: low to high contact angle, D: short to long duration; P: adhesion D: low to high, D: contaminant type; P: roughness D: slight to distinctive cell convexity, D: type of geometry (convex, papillose and hairy); P: waxiness D: thin to thick)

Table 130: Summary of potential concepts, properties and dimensions for Neinhuis 1997

Concepts	Properties	Dimensions
Epidermal microstructures	Water-repellency	Low to high contact angle
		Short to long in duration
	Anti-adhesion	Low to high
		Contaminant type
	Roughness	Slight to distinctive cell convexity
		Type of geometry (convex, papillose and hairy)
	Waxiness	Thin to thick

Coder	John Reap	Date	6/7/2007
Text Segment	Paragraphs: abstract to para. 5	Type	Memo
Reference	Newell, Sandra Jo and Elliot J. Tramer. (1978) "Reproductive Strategies in Herbaceous Plant Communities During Succession" *Ecology* 59 (2): 228-234.		

"…life history strategies as attempts to optimize allocation of resources among maintenance, growth and reproduction."

A number of ecologically interesting concepts appear in the abstract and first paragraphs. One sees reproductive strategy, r-strategy, K-strategy, life history strategy and succession. The first four concepts define organisms or populations of organisms, while the final one provides a term for the process of ecosystem development. Reproductive strategies have the property of reproductive effort which varies between low and high. The authors use the ratio of dry reproductive biomass to total dry biomass to quantify reproductive effort. Life history strategy appears to be a collection of traits; these traits are properties. The authors list reproductive effort, reproductive life span, age at reproduction, degree of parental care and fecundity as properties of a life strategy. Obvious dimensions for these terms include low to high and long to short.

Succession would seem to have properties reflecting the collective or average life history strategies of an ecosystem's inhabitants. Reproductive pattern might be such a property, which one would dimension by type (constant, synchronous, random, etc.). Other average factors are needed to define this concept, but the authors focus on reproduction in the first paragraphs.

Potential Concepts: reproductive strategy (P: reproductive effort D: low to high), r-strategy, K-strategy, life history strategy (P: reproductive effort D: low to high; P:

reproductive life span D: short to long; P: age of first reproduction D: time; P: degree of parental care D: low to high; P: fecundity D: low to high), succession (P: reproductive pattern D: type)

Text Segment	Paragraphs: 20-26	Type	Memo

"…data indicate a shift in reproductive strategies of herbaceous plants during succession."

On the surface, the authors discuss reproductive strategies in this section, but their discussion of reproductive strategies reveals properties that describe the successional state of a community. Properties such as <u>reproductive effort</u>, <u>energy storage</u>, <u>offspring production</u> and <u>life span</u> combine with reproductive pattern to help one describe the successional state of communities. These new properties of succession may be respectively dimensioned by <u>low to high</u>, <u>low to high</u>, <u>number</u> and <u>long to short</u>. Based on the authors work, it seems safe to say that a mature ecosystem is primarily composed of long-lived organisms that store significant amounts of energy while expending little reproductive effort producing few seeds at a relatively constant rate.

Now, this is powerful stuff. Here, we have the beginnings of an energetic or material based classification system for an enterprise, community or even society. We even have a few metrics such as reproductive biomass to total biomass ratio and stored energy that one might use to classify human systems. Of course, ideas related to r- and K- strategy are well known in industrial ecology; so, the contribution would need to be more substantial than simply rehashing the idea.

Potential Concepts: reproductive strategy (P: reproductive effort D: low to high), r-strategy, K-strategy, life history strategy (P: reproductive effort D: low to high; P: reproductive life span D: short to long; P: age of first reproduction D: time; P: degree of parental care D: low to high; P: fecundity D: low to high), succession (P: reproductive pattern D: type; P: reproductive effort D: low to high; P: offspring production D: low to high; P: energy storage D: low to high; P: life span D: long to short)

Table 131: Summary of potential concepts, properties and dimensions for Newell 1978

Concepts	Properties	Dimensions
Life history strategy	Reproductive effort	Low to high
	Reproductive life span	Short to long
	Age of first reproduction	Time
	Degree of parental care	Low to high
	Fecundity	Low to high
Succession	Reproductive pattern	Type (i.e. constant, synchronous, random)
	Reproductive effort	Low to high
	Energy storage	Low to high
	Offspring production	Number
	Life span	Long to short
K-strategy	?	?
r-strategy	?	?
Reproductive strategy	Reproductive effort	Low to high

Coder	John Reap	Date	7/20/2007
Text Segment	Paragraphs: 1-p. 241	Type	Memo
Reference	Norris, V. et al. (2007) "Functional Taxonomy of Bacterial Hyperstructures." *Microbiology and Molecular Biology Reviews* 71 (1): 230-253.		

"…a level of organization exists midway between genes/proteins and whole cells. This is the level of the hyperstructure…"

The <u>hierarchy</u> concept pervades the first two thirds of this paper. They <u>hyperstructure</u> concept discussed by the authors is simply a hierarchical level found between that of macromolecules such as proteins and cells. Are hyperstructures smaller than organelles? The processes discussed by the authors seem to be smaller than organelles; the nucleolus is smaller than the nucleus for instance. It seems that hyperstructures exist in the size gap between organelles and proteins. These macromolecular assemblies do possess the property of <u>transience</u> which allows them to have either <u>equilibrium or nonequilibrium</u> status.

The authors list and discuss multiple potential hyperstructures, but I find the dense macromolecular discourse impenetrable. Their sections on hyperstructure processes is equally difficult to understand.

Potential Concepts: hierarchy, hyperstructure (P: transience D: equilibrium or nonequilibrium)

Table 132: Summary of potential concepts, properties and dimensions Norris 2007

Concepts	Properties	Dimensions
Hyperstructure	Transience	Equilibrium or nonequilibrium
Hierarchy	?	?

Coder	John Reap	Date	7/30/2007
Text Segment	Paragraphs: abstract -2	Type	Memo
Reference	Nowak, Martin (2006) "Five Rules for the Evolution of Cooperation" *Science* 314: 1560-1563.		

"Cooperation is needed for evolution to construct new levels of organization…But natural selection implies competition and therefore opposes cooperation unless a specific mechanism is at work."

Many of the major and encompassing ideas in biology appear in the abstract: evolution, selection, and organism interactions. Type is the focal property of organism interactions in this work, and it varies between competition and cooperation. How can cooperative organism interactions evolve when natural selection favors competition? This is the central question. One learns that the author intends to investigate this question by discussing five concepts with associated metrics capable of explaining this evolutionary contradiction.

Before proceeding, it is helpful to define a few of the terms encountered in this paper.

> Cooperator – an individual that contributes resources or "pays a cost," c, in order that another may gain a benefit, b
>
> Defector – an individual that does not contribute resources or produce benefits

Potential Concepts: evolution, selection, organism interactions (P: type D: competition and cooperation)

Text Segment	Paragraphs: 3-4	Type	Memo

"…natural selection can favor cooperation if the donor and the recipient of an altruistic act are genetic relatives."

In the author's eyes, Kin selection is the appropriate title and first concept capable of overcoming natural selection's bias toward competition. Relatedness might be the correct property to associated with this concept; it varies dimensionally according to the coefficient of relatedness, r. The relatedness coefficient is simply the cost to benefit ratio for a cooperative organism interaction.

$$r > c/b$$

Potential Concepts: evolution, selection, organism interactions (P: type D: competition and cooperation), kin selection (P: relatedness D: coefficient of relatedness)

Text Segment	Paragraphs: 5-9	Type	Memo

"…cooperation between unrelated individuals or…different species…led Trivers to propose another mechanism for the evolution of cooperation, direct reciprocity."

Direct reciprocity is a cooperative strategy in which one entity chooses to cooperate at time t in the expectation that the other entity will cooperate at time t+1. Such behavior only seems reasonable if both entities meet again, meaning that encounter likelihood is a potential property. It would vary dimensionally cooperation probability, w. The author argues that direct reciprocity's effectiveness is measured according to the following ratio that relates encounter likelihood to the cost and benefits for a particular act.

$$w > c/b$$

Potential Concepts: evolution, selection, organism interactions (P: type D: competition and cooperation), kin selection (P: relatedness D: coefficient of relatedness), direct reciprocity (P: encounter likelihood D: cooperation probability; P: effectiveness D: w>c/b)

Text Segment	Paragraphs: 10-end	Type	Memo

Three other cooperation concepts are described in this article: indirect reciprocity, network reciprocity and group selection. Each has an associated cost to benefit formula that provides information about the particular rule's ability to encourage cooperative behavior. When comparing the five mechanisms for cooperation, the author introduces a new property for organism interactions – effectiveness. Effectiveness' dimensions are discrete and include: excluded, evolutionary stability, risk dominant, advantageous and dominant.

Potential Concepts: evolution, selection, organism interactions (P: type D: competition and cooperation; P: effectiveness D: excluded to dominant), kin selection (P: relatedness D: coefficient of relatedness), direct reciprocity (P: encounter likelihood D: cooperation probability; P: effectiveness D: w>c/b), indirect reciprocity, network reciprocity, group selection

Table 133: Summary of potential concepts, properties and dimensions Nowak 2006

Concepts	Properties	Dimensions
Evolution	?	?
Selection	?	?
Organism interactions	Type	Competition to cooperation
	Effectiveness	Excluded to dominant (see text)
Kin selection	Relatedness	Coefficient of relatedness
Direct reciprocity	Encounter likelihood	Cooperation probability
	Effectiveness	W > c/b
Indirect reciprocity	?	?
Network reciprocity	?	?
Group selection	?	?

Coder	John Reap	Date	6/27/2007
Text Segment	Paragraphs: abstract - 10	Type	Memo
Reference	Nystrom, M., C. Folke and F. Moberg (2000) "Coral reef disturbance and resilience in a human-dominated environment" *Trends in Ecology and Evolution* 15 (10): 413-417.		

"…reefs are now seen as dynamic systems subject to natural disturbances…much research has focused on the ability of reefs to recover to their original state…"

This passage contains the articles two main concepts – <u>disturbance</u> and <u>resilience</u>. In the second paragraph, the authors list the main properties of a disturbance: <u>magnitude</u>, <u>duration</u>, <u>frequency</u>, and <u>spatial distribution</u>. A table in their article lists disturbances ranging from predation to sea level change; so, to those listed in the article, I would add <u>type</u>. Based on the information in said table, the dimensions for these properties would respectively be <u>low to high</u>, <u>short to long</u>, <u>low to high</u> and <u>local to global</u>. The authors statements lead the reader to believe that global scale moderate to high magnitude disturbances with long durations that frequently occur are the most troublesome for coral reef ecosystems. This is hardly a surprise.

Resilience is loosely defined as the reef's ability to return to a prior state once disturbed. Some statements are made about shifting equilibriums and alternate stable states. The authors use the example of coral vs. algae dominated reef ecosystems. However, properties for resilience are not clearly present in the opening paragraphs.

<u>Climax systems</u> are mentioned in the first paragraph. This idea is connected with the concept of <u>succession</u> mentioned in other articles. In fact, a climax system is part of a dimension of succession. If we assign the property of <u>level</u> to the concept succession, one of its dimensions would vary from <u>pioneer to climax systems</u>.

Potential Concepts: disturbance (P: magnitude D: low to high; P: duration D: short to long; P: frequency D: low to high; P: spatial distribution D: local to global; P: type D: by disturbance), resilience, succession (P: level D: pioneer to climax systems)

Text Segment	Paragraphs: 11-end	Type	Memo

"The capacity of ecosystems to cope with disturbance is determined by characteristics such as genetic variability within populations, diversity within and among functional groups, and variability and connectedness of habitats."

In some of these latter paragraphs, one sees more discussion of the characteristics responsible for resilience as well as a few examples of coral reef systems weakened to the point where they lost most of their resilience. Genetic diversity, functional diversity and connectedness all influence resilience, but they are not strictly properties of resilience. The idea of a stability domain is, however, a property of resilience that varies dimensionally from small to large. This property comes from a paper by C.S. Holling that is worth retrieving and potentially coding. A stability domain is the magnitude of a disturbance a system can absorb before shifting from one stable state to another.

Potential Concepts: disturbance (P: magnitude D: low to high; P: duration D: short to long; P: frequency D: low to high; P: spatial distribution D: local to global; P: type D: by disturbance), resilience (P: stability domain D: small to large), succession (P: level D: pioneer to climax systems)

Table 134: Summary of potential concepts, properties and dimensions Nystrom 2000

Concepts	Properties	Dimensions
Disturbance	Magnitude	Low to high
	Duration	Short to long
	Frequency	Low to high
	Spatial distribution	Local to global
	Type	By disturbance (i.e. hurricane, global warming, etc.)
Resilience	Stability domain	Small to large
Succession	Level	Pioneer to climax

Coder	John Reap	Date	3/11/2007
Text Segment	Chapter 6: p. 175-179	Type	Memo
Reference	Odum, E. P. (1997). Ecology: A Bridge Between Science and Society. Sunderland, Sinauer Associates.		

"…during early colonization...natural selection pressure favors species with high reproductive potentials (large investment in offspring…crowded conditions favor…greater capabilities for utilizing and competing for scarce resources…"

A number of noteworthy concepts appear on these pages. Carrying capacity, "…the theoretical maximum sustainable density…," provides the context for the development of other concepts in this section. Carrying capacity is usually measured in terms of biomass or numbers of organisms, though social scientists add "intensity of use" when considering the carrying capacity of humans. A few pages earlier, carry capacity is given the property of adjustability. It seems that interactions between organisms and their environment change theoretical maximums. One might think of carrying capacity as being rigid to adjustable. When I think of adjustability, I think of knobs, levers, sliders or other means of varying some controllable quantity. It would be interesting to understand the quantities that change when organisms increase or decrease an environment's carrying capacity. Understanding the adjustment process might also prove enlightening.

Having set carrying capacity as a context, the author introduces r-strategist and K-strategist. Both share the properties reproductive biomass and maintenance biomass which can vary dimensionally between high and low. In fact, these properties define r and K strategists. The former combines high reproductive biomass with comparatively low maintenance biomass while the latter is denoted by the opposite biomass assignment.

Now, I know that the biomimetic and industrial ecology communities have explored different meanings for r and K strategies in engineering, and some work in MFA aims to quantify these ideas. It might be worth attempting to find and axially code articles devoted to r and K resource utilization strategies in biology.

Potential Concepts: carrying capacity (P: adjustability D: rigid to adjustable; P: biomass D:?; P: number D: ?), r-strategist (P: reproductive biomass D: high to low; P: maintenance biomass D: high to low), k-strategist (P: reproductive biomass D: high to low; P: maintenance biomass D: high to low)

Text Segment	Chapter 6: p179-182	Type	Memo

"…a population partitions energy among various activities…"

Energy and its acquisition dominate this short section. The concepts of <u>existence energy</u> and <u>net energy</u> appear. Both are terms used by the author. Another concept also floats in the background of the discussion about spiders and space. <u>Energy acquisition strategies</u> seem to have the property <u>type</u> which varies dimensionally from <u>hunt</u> to <u>collect</u>. The idea of territoriality seems connected to both hunting and collecting, but I cannot see the connection using the concept, property, dimension approach at this time.

Potential Concepts: existence energy, net energy, energy acquisition strategies (P: type D: hunt to collect)

Table 135: Summary of potential concepts, properties and dimensions for Odum 1997 #1

Concepts	Properties	Dimensions
Carrying capacity	Adjustability	Rigid to adjustable
	Biomass	?
	Number	?
r-strategist	Reproductive biomass	High to low
	Maintenance biomass	
K-strategist	Reproductive biomass	High to low
	Maintenance biomass	
Existence energy	?	?
Net Energy	?	?
Energy acquisition strategy	Type	Hunt to collect

Coder	John Reap	Date	3/11/2007
Text Segment	Chapter 6: p. 187-	Type	Memo
Reference	Odum, E. P. (1997). Ecology: A Bridge Between Science and Society. Sunderland, Sinauer Associates.		

"…effect that one species may have on the population…of another species may be negative (-), positive (+), or neutral (0)."

The main introduced concepts deal with the net influence of interactions between species as measured by population variables such as size and growth. Biologists name a number of the nine possible interactions presented by the quoted +, 0, - model. Here, I list and define them using Odum's own words:

> **Competition** (-,-): both populations inhibit or have some kind of negative effect on each other
>
> **Predation** (+,-): positive for the predator, negative for the prey
>
> **Parasitism** (-,+): negative for the host, positive for the parasite
>
> **Commensalism** (+,0): one species, the commensal, benefits, the other is not affected
>
> **Cooperation** or **mutualism** (+,+): both populations benefit from the interaction, which may be optional (cooperation) or essential for the survival of both partners (mutualism)

Named interactions are clearly concepts. Competition has the properties of intraspecific and interspecific, which refer to competition between members of the same species and of different species, respectively. One might give both the same dimension of intensity or variation from low to high. Predation possesses the property of control. Predation directly influences prey population and indirectly influences other species by allowing them to populate habitats freed of prey. Therefore, one might give control the dimensions of indirect to direct. Parasitism possesses the property of species specificity which varies from low to high. Most parasites display a high degree of species specificity. Commensalism and cooperation are fascinating concepts that hold great meaning for industrial ecology. On more than one occasion, Odum does state that cooperation is extremely important, but this chapter seems to provide little beyond an explanation of the ideas with supporting examples.

Competitive exclusion (a.k.a: Gause's principle or ecological separation) appears in Odum's discussion of competition. However, his account of experiments with flour beetles does not immediately reveal any properties. It does illustrate the importance of environmental factors. Might one potential property of competitive exclusion be environmental influence? Interestingly, he cites sources such as den Boer who believe that some degree of coexistence is the "rule" in ecosystems and competitive exclusion is the "exception."

Potential Concepts: competition (P: intraspecific D: low to high; P: interspecific D: low to high), predation (P: control D: indirect to direct), parasitism (P: species specificity D: low to high), commensalim, cooperation

Concepts	Properties	Dimensions
Competition	Intraspecific	Low to high
	Interspecific	Low to high
Predation	Control	Indirect to direct
Parasitism	Species specificity	Low to high
Predation	?	?

Commensalism	?	?
Cooperation	?	?
Energy acquisition strategy	Type	Hunt to collect

Table 136: Summary of potential concepts, properties and dimensions for Odum 1997 #2

Coder	John Reap	Date	6/16/2007
Text Segment	Paragraphs: abstract-2	Type	Memo
Reference	Ostfeld, R.S. and F. Keesing (2000) "Pulsed resources and community dynamics of consumers in terrestrial ecosystems" *Trends in Ecology and Evolution* 15 (6): 232-237.		

"…effects of pulsed resources on consumer communities integrate 'top-down' and 'bottom-up' approaches to community dynamics..."

Production / resource pulses and community dynamics are the first two concepts in this paper. Control is a property of community dynamics; it varies dimensionally by type (top-down, bottom-up and competition within a trophic level). How exactly a resource pulse influences communities appears to be an area of ongoing research in ecology.

Potential Concepts: production / resource pulse, community dynamics (P: control D: type)

Text Segment	Paragraphs: 3-end	Type	Memo

"…resource pulses occur as episodic events with long interpulse intervals..."

Periodicity appears to be a property of resource pulses, and it varies dimensionally from periodic to sporadic. It should be noted that the authors seem to regard only sporadic resource inputs as true pulses, though some ambiguity is introduced in the conclusion. Food webs lay barely concealed beneath the surface of these later paragraphs. The authors' discussion of generalist consumers brings them to the fore. Generalists are most capable of utilizing the excess biotic production made available during a pulse. This fact means that a food web's composition, which varies dimensionally by species (i.e. generalists), affects its response to a resource pulse.

Potential Concepts: production / resource pulse, community dynamics (P: control D: type), food web (P: composition D: by species)

Table 137: Summary of potential concepts, properties and dimensions for Ostfeld 2000

Concepts	Properties	Dimensions
Food web	Composition	By species (i.e. generalist)
Community dynamics	Control	Type (top-down, bottom-up and competition within a trophic level)
Production / resource pulse	Periodicity	Periodic to sporadic

Coder	John Reap	Date	7/2/2007
Text Segment	Paragraphs: 1-12	Type	Memo
Reference	Power, Mary E., D. Tilman, J.A. Estes, B.A. Menge, W.J. Bond, L.S. Mills, G. Daily, J.C. Castilla, J. Lubchenco and R.T. Paine (1996) "Challenges in the Quest for Keystones" *BioScience* 46 (8): 609-620.		

"…less abundant species, often called keystone species, also have strong effects on communities and ecosystems."

This paper's major concepts appear in its first 12 paragraphs. Abundant species and keystone species, the central concepts, are introduced in the first paragraph. Abundant species strongly influence an ecosystem by providing energy flows and habitat. In contrast, keystones influence a species to a greater extent than suggested by their abundance and biomass. Both concepts clearly have the property of influence which varies by type (i.e. productivity, nutrient cycling, species richness, etc.) and magnitude or community index (CI).

The top-down control concept appears on the third page. Keystone species seem to be one of the primary agents of top-down control.

Potential Concepts: abundant species (P: influence D: type, magnitude or community index), keystone species (P: influence D: type, magnitude or community index), top-down control

Table 138: Summary of potential concepts, properties and dimensions for Power 1996

Concepts	Properties	Dimensions
Abundant species	Influence	Type (i.e. productivity, nutrient cycling, species richness, etc.)
		Magnitude or community index (CI)
Keystone species	Influence	Type (i.e. productivity, nutrient cycling, species richness, etc.)
		Magnitude or community index (CI)
Top-down control	?	?

Coder	John Reap	Date	7/10/2007
Text Segment	Paragraphs: abstract - 3	Type	Memo
Reference	Quenette, P.Y. (1993) "Why biologists do not think like Newtonian physicists" *Oikos* 68(2): 361-363.		

"When we have an evolutionary perspective on a system, we mean that we are interested in the changes of state of this system in time, each state being specified by a state variable."

This little article uses yet does not better define a number of big concepts in biology. As this quotation reveals, concepts such as evolution, natural selection and contingency appear in the text. Contingency, the random events in the evolutionary history of an organism, possesses the property of influence which varies dimensionally from low to high. Evolution and natural selection are not well defined. The author primarily uses these ideas to counter a Newtonian view of ecology espoused by another author in an earlier paper.

The concepts of dissipative structures and self-organization from non-equilibrium thermodynamics also find a place in this article.

Potential Concepts: evolution, natural selection, contingency (P: influence D: low to high), dissipative structures, self-organization

Table 139: Summary of potential concepts, properties and dimensions for Quenette 1993

Concepts	Properties	Dimensions
Evolution	?	?
Natural selection	?	?
Contingency	Influence	Low to high
Dissipative structures	?	?
Self-organization	?	?

Coder	John Reap	Date	6/17/2007
Text Segment	Paragraphs: abstract-5	Type	Memo
Reference	Rainey, P.B., A. Buckling, R. Kassen and M. Travisano (2000) "The emergence and maintenance of diversity: insights from experimental bacterial populations" in *Trends in Ecology and Evolution* 15 (6): 243-247.		

"Recent studies reveal the circumstances and mechanisms that promote the emergence of stable polymorphisms."

The concept of diversity is defined by properties of maintenance and generation. Dimensions for maintenance are not clear in the first paragraphs, but rate and mechanism are clearly dimensions for generation. According to the authors, the mechanisms capable of generating diversity are "selection, mutation and genetic drift." They focus on selection.

The competitive exclusion principle also appears as a concept in the opening paragraphs.

Potential Concepts: Diversity (P: maintenance D: ?; P: generation D: rate, mechanism), competitive exclusion principle

Text Segment	Paragraphs: 6-8	Type	Memo

"…emergence of a stable polymorphism involving cross-feeding has been observed in *E. coli* populations..."

Rather unexpectedly in an article about polymorphism generation in bacteria, a concept called cross-feeding emerges. Cross-feeding is the "waste=food" concept from industrial ecology. The authors cite prior work that described the evolution of different strains of *E. coli* bacteria that could consume each others wastes.

Potential Concepts: Diversity (P: maintenance D: ?; P: generation D: rate, mechanism), competitive exclusion principle, cross-feeding

Text Segment	Paragraphs: 9-15	Type	Memo

"…temporal, as well as spatial factors, play a role in maintaining diversity in this model system…"

Environmental heterogeneity breeds organism heterogeneity is a concept that emerges from the middle paragraphs. Bacterial tests using homogenous and heterogeneous environments recounted by the authors support the existence of this concept.

Potential Concepts: Diversity (P: maintenance D: ?; P: generation D: rate, mechanism), competitive exclusion principle, cross-feeding

Table 140: Summary of potential concepts, properties and dimensions for Rainey 2000

Concepts	Properties	Dimensions
Diversity	Generation	Rate
		Mechanism (selection, mutation, genetic drift)
	Maintenance	?
Competitive exclusion principle	?	?
Cross-feeding	?	?
Environmental heterogeneity breeds organism heterogeneity	?	?

Coder	John Reap	Date	7/18/2007
Text Segment	Paragraphs: abstract-7	Type	Memo
Reference	Rooney, N., K. McCann, G. Gellner and J.C. Moore (2006) "Structural asymmetry and the stability of diverse food webs." *Nature* 442: 265-269.		

"…real food webs are structured such that top predators act as couplers of distinct energy channels that differ in both productivity and turnover rate."

Rooney's article adds unique insights to the body of knowledge surrounding the ecological concepts of <u>food webs</u> and <u>biodiversity</u>. Food webs have properties of <u>structure</u>, <u>productivity</u>, <u>stability</u> and <u>persistence</u>. Structure varies by <u>type</u> (i.e. modular or "compartmental) and <u>symmetry</u>; productivity varies from <u>low to high</u>. Types of food web structures found seem to be highly asymmetric. Stability is better defined in later paragraphs and will not be discussed, here. Persistence is not given significant attention beyond the abstract.

The <u>Energy channel</u> concept is, thus far, unique to these authors. They possess the properties of <u>productivity</u> and <u>turnover rate</u> which one measures in terms of <u>biomass growth rate</u> and <u>biomass growth rate : biomass stock ratio</u>, respectively. The authors contend that the presence of "slow" (low growth rate and ratio) and "fast" (high growth rate and ratio) energy channels improve ecosystem stability.

Potential Concepts: food web (P: structure D: type, symmetry; P: productivity D: low to high; P: stability D: ?; P: persistence D: ?), biodiversity, energy channel (P: productivity D: biomass growth rate; P: turnover D: biomass growth rate : biomass stock ratio)

Text Segment	Paragraphs: 8-11	Type	Memo

"…local stability, as measured by the most negative eigenvalue…non-local stability defined as return speed divided by overshoot."

In these central paragraphs, one finds dimensions for the property of stability. Eigenvalue and transient non-equilibrium stability serve as measures for two different kinds of food web stability. Eigenvalue applies under equilibrium conditions while transient non-equilibrium stability is used to assess the capacity of a food web to return to a prior state following perturbation – resilience.

Potential Concepts: food web (P: structure D: type, symmetry; P: productivity D: low to high; P: stability D: eigenvalue, transient non-equilibrium stability; P: persistence D: ?), biodiversity, energy channel (P: productivity D: biomass growth rate; P: turnover D: biomass growth rate : biomass stock ratio)

Text Segment	Paragraphs: 11-end	Type	Memo

One can state the authors' conclusions using the codes in the previous paragraphs. Food webs are both statically and dynamically more stable if their structures are highly asymmetric in terms of energy channel. Large differences in energy channel as evidenced by different growth rates and turnover ratios promote ecosystem stability as measured by eigenvalue and trans. Non-equib. stab. Coupling of these different energy channels by a consumer is also important.

Table 141: Summary of potential concepts, properties and dimensions for Rooney 2006

Concepts	Properties	Dimensions
Food web	Structure	Type
		Symmetry
	Productivity	Low to high
	Stability	Eigenvalue
		Transient non-equilibrium stability
	Persistence	?
Biodiversity	?	?
Energy channel	Productivity	Biomass growth rate
	Turnover	Biomass growth rate : biomass stock ratio

Coder	John Reap	Date	3/8/2007
Text Segment	Paragraphs: abstract to p. 1090	Type	Memo
Reference	Ryall, Krista L. and Lenore Fahrig "Response of Predators to Loss and Fragmentation of Prey Habitat: A Review of Theory." *Ecology* 85 (5): 1086-1093.		

"…the effects of habitat loss and fragmentation on predator-prey interactions..."

Though specifically discussing predator-prey relationships and habitat, this article is conceptually about interactions and resource collapse. The authors focus on two nodes, prey and predators, in a food web network. They review literature discussing the influence of habitat loss and fragmentation on these nodes and the interaction between them. Essentially, they are studying the influence of context on network interactions. The investigation includes examination of specialist, omnivorous and generalist predators; so, they are also classifying the connectivity of the predator node in the network.

Nodes and node persistence are at the forefront of their discussions, and node persistence is almost certainly a central concept. Connectivity plays a central role in determining the persistence of predator nodes. Therefore, it seems to be a property of nod persistence with the dimensions of few to many connections. One could consider habitat as supporting infrastructure for the network, making infrastructure support another property of node persistence with the dimensions of low to high. Not surprisingly, the predator node that persists in the presence of low infrastructure support in a particular area is the one with many connections.

Potential Concepts: node persistence (P: connectivity D: few to many; P: infrastructure support D: low to high)

Table 142: Summary of potential concepts, properties and dimensions for Ryall

Concepts	Properties	Dimensions
Node persistence	Connectivity	Few to many
	Infrastructure support	Low to high

Coder	John Reap	Date	6/18/2007
Text Segment	Paragraphs: abstract-17	Type	Memo
Reference	Sachs, J.L. and E.L. Simms (2006) "Pathways to mutualism breakdown" *Trends in Ecology and Evolution* 21(10): 385-392.		

"Models predict that mutualists…evolve into parasites,…live autonomously…also vulnerable to extinction."

As the title states, this paper discusses mutualism and the ways in which it might cease to exist. Mutualism is defined as an interaction between two species which benefits both. A number of properties for mutualism are apparent. Relationship, benefit and dependency help define this concept. Byproduct mutualism and reciprocity are the two types of relationships leading to stable mutualisms. In byproduct mutualism, the beneficial interaction comes without cost to the two species, and in a reciprocal situation, two species intentionally cooperate to reap mutual benefits. These types serve as dimensions for this property. Benefit seems to vary dimensionally by magnitude (often measured using a "cost:benefit ratio") and type. Interestingly, the authors list a number of conditions under which the cost:benefit ratio becomes unfavorable:

- Mutualistic partners difficult to locate
- Partners are poor match
- Third parties disrupt the mutual arrangement through parasitism
- Benefits of mutualism become readily available from the environment

Dependency describes the degree to which interaction has become necessary for a pair of species, and it varies from facultative (useful under some circumstances, though not necessary) to obligate (necessary).

Mutualism breakdown might be a concept. Its properties would seem to by type and frequency. The types of breakdowns mentioned in this article are parasitism and return to autonomy. The dimensions for frequency are not clear; for organism, they seem related to the evolutionary occurrence of each type of breakdown.

Feedback is a concept closely associated with mutualism in this piece. The authors mention the idea of "sanctioning" a partner organism on more than one occasion. Sanctioning, a form of usually material or energetic feedback, seems to occur when a partner does not fully uphold its part of the arrangement.

Potential Concepts: mutualism (P: relationship D: byproduct to reciprocity; P: benefit D: magnitude, type; P: dependency D: facultative to obligate), feedback, mutualism breakdown (P: Type D: parasitism to return to autonomy; P: frequency D: ?)

Table 143: Summary of potential concepts, properties and dimensions for Sachs 2006

Concepts	Properties	Dimensions
Feedback	?	?
mutualism	Benefit	Magnitude (often measured using a "cost:benefit ratio")
		Type
	Dependency	Facultative (useful under some circumstances, though not necessary) to obligate
	Relationship	Byproduct to reciprocity
Mutualism breakdown	Type	Parasitism to return to autonomy
	Frequency	?

Coder	John Reap	Date	6/14/2007
Text Segment	Pages: 1559-1567	Type	Memo
Reference	Schoener, Thomas H. (1989) "Food Webs from the Small to the Large" *Ecology* 70 (6): 1559-1589.		

"…the importance of competition vs. predation alternates in a terrestrial food web..."

Population control is a concept that dominates the first part of this paper, and it remains an important theme for the entire work. The authors state two different hypotheses for the mechanisms that govern population control. Mechanism, therefore, seems to be a property of population control. Effectiveness would also seem to be a property, but the authors do not concern themselves with it here. Mechanism's dimensions correspond to the different hypothesized types of population control: predation, competition and physical disturbance. Control at alternating trophic levels by predation and competition corresponds to the "HSS" hypothesis while control of the "top" trophic level by physical disturbances corresponds to the "MS" hypothesis. Note, HSS and MS designations are entirely the author's choice and are not standard references in the literature. The quoted passage also reveals the importance context. The rules for population control seem to vary somewhat in different environments. One might then say that context is a property of population control that varies dimensionally by environment.

The food web concept provides context for the entire article, and many previously encountered food web properties appear in the first eight pages. These properties include size and connectance. This author estimates food web size in terms of trophic elements (See paper for def.). In other memos, I refer to food web structure as a concept. Food web structure is a subordinate concept to food web, yet I assign the same properties to both. I may need to resolve this tension in the future.

Potential Concepts: Population control (P: mechanism D: type; P: context D: by environment), food web (P: size D: trophic element; P: connectance D: ?)

Text Segment	Paragraphs: para. 1567-1573	Type	Memo

"…we ask what contribution our research might make to a theory of food-chain length..."

Food chain appears as a new concept in this section. Length is one obvious property that the authors introduce early in their discussion of food chains. It varies dimensionally from short to long. One should note that length is often quantified using maximum chain length, which is the number of links between basal (not consuming prey) and top (not preyed upon) trophic species.

Most of this section is devoted to discussions and citation of evidence focused on different hypotheses relating food chain length to productivity and "dimensionality." Of course, this raises the question productivity and dimensionality of what? It is clear that productivity and dimensionality are properties of food webs, and in the case of productivity, it is a property not properly placed beneath the food web structure concept. Productivity varies dimensionally from low to high, but how would one vary food web dimensionality? Variation by number of dimensions comes to mind. The authors note that a forest would have higher "dimensionality" than a grass land; so, one might think of dimension number in terms of the number of axes available for growth and hunting. Grasslands would be two dimensional while forests would have a third dimension.

Potential Concepts: Population control (P: mechanism D: type; P: context D: by environment), food web (P: size D: trophic element; P: connectance D: ?; P: productivity D: low to high; P: dimensionality D:?), food chain (P: length D: short to long)

Text Segment	Paragraphs: para. 1583-1586	Type	Memo

"…various kinds of systems show both surprising similarities and substantial differences in food-web properties."

The final pages of this work witness the proposition of a plethora of food web properties. Size, maximum chain length, "Loose-knitness," vulnerability, fraction basal species all appear or reappear. The latter four vary dimensionally from low to high. Ways of measuring and comparing low and high appear in the paper. In contrast to statements about these terms in prior sections, the author expresses belief in the value of many of these terms for food webs in multiple environments.

Potential Concepts: Population control (P: mechanism D: type; P: context D: by environment), food web (P: size D: trophic element; P: connectance D: ?; P: productivity D: low to high; P: dimensionality D:?; P: maximum chain length D: low to high; P: loose-knitness D: low to high; P: vulnerability D: low to high; P: fraction basal species D: low to high), food chain (P: length D: short to long)

Table 144: Summary of potential concepts, properties and dimensions for Schoener 1989

Concepts	Properties	Dimensions
Population Control	Mechanism	Type (predation, competition and physical disturbance)
	Context	By environment
Food web	Size	Trophic element
	Connectance	?
	Productivity	Low to high
	Dimensionality	Number of dimensions
	Maximum chain length	Low to high
	Loose-knitness	Low to high
	Vulnerability	Low to high
	Fraction basal species	Low to high

Coder	John Reap	Date	3/8/2007
Text Segment	Abstract	Type	Memo
Reference	Schonborn, Wilfried (2003) "Defensive reactions of freshwater ecosystems against External influences" *Limnologica* 33: 163-189.		

Defense reactions are both the theme of this paper and a concept. They seem to possess the properties of scale and motivation. In the process of introducing defensive reactions, the author mentions three organizational levels (organism, compartment and ecosystem) on which they occur; organizational level seems to be a dimension of scale in this context. Motivation's dimensions vary between egoistic and altruistic. Egoistically motivated defense reactions create positive benefits for the system as a side effect while altruistically motivated ones seem to occur for "the good of the system." It seems quite unreasonable that compartments or ecosystems have motivations; so, this particular property may only apply at the scale and organizational level associated with organisms. But, how would the organism know that it needs to "take one for the team"?

Potential Concepts: defense reactions (P: scale D: organizational level; P: motivation D: egoistic to altruistic)

Text Segment	Paragraphs: "Summary" p. 183-185	Type	Memo

"…terrestrial outlet mechanisms by food chains from freshwater organism to terrestrial consumer…"

Defense reactions discussed by the author primarily occur in response to toxic or excessive nutrient loading. They seem to fall into the categories of material removal, substance concentration and input resistance. Material removal seems to have properties such as path type, path number and magnitude. The path type is dimensioned by the organism responsible for removing the particular toxin or nutrient, while path number would seem to vary from few to many. His statement about the ineffectiveness of nutrient removal by marine eels supports the idea that magnitude has the obvious dimensions of small to large. Properties and dimensions for substance concentration and input resistance are not entirely clear.

It is interesting to note that the author believes that the number of freshwater ecosystem defense "mechanisms" / reactions positively correlates with ecosystem stability. I wonder if one might find a similar correlation with urban environments or industrial parks?

Potential Concepts: material removal (P: path type D: responsible organism; P: path number D: few to many; P: magnitude D: small to large), substance concentration, input resistance

Table 145: Summary of potential concepts, properties and dimensions for Schonborn 2003

Concepts	Properties	Dimensions
Defense reactions	scale	Organizational levels
	motivation	Egoistic to altruistic
Material removal	Path type	Responsible organism
	Path number	Few to many
	Magnitude	Small to large
Substance concentration	?	?
Input resistance	?	?

Coder	John Reap	Date	6/16/2007
Text Segment	Paragraphs: 1-7	Type	Memo
Reference	Sears, A.L.W., R.D. Holt and G.A. Polis. "Feast and Famine in Food Webs: The Effects of Pulsed Productivity" in *Food Webs at the Landscape Level*. (2004) G.A. Polis, M.E. Power and G.R.Huxel Eds. University of Chicago Press: London.		

"…for the most part descriptions of food webs have been closed in space and static in time."

This article focuses on the food web concept's properties of productivity and dynamics. Specifically, the authors seem intent on exploring the influence of dynamics on productivity. They introduce the idea of food web subsidies, which seem to be biotic or abiotic inputs of material, energy and organisms from beyond the confines of the studied food web. Subsidies are defined by type, frequency, and control. Subsidy types vary dimensionally from biotic to abiotic, though classification by material, energy and living may also be useful. Frequency varies from static to frequent, and control is either recipient or donor controlled.

Potential Concepts: food web (P: productivity D: low to high; P: dynamics D: ?), subsidies (P: type D: biotic to abiotic; P: frequency D: static to infrequent; P: control D: recipient or donor controlled)

Text Segment	Page 373, paragraph 1	Type	Memo

"Another approach to analyzing environmental fluctuations is to perform a spectrum analysis on time series data."

Has anyone performed a spectral analysis on an industrial eco-park? Can one perform such an analysis? "Most population dynamics are white or red," where white corresponds to random variation and red to slow dynamics. What "colors" would a spectral analysis of an eco-park reveal?

Text Segment	Page 375-376, paragraph 2-4	Type	Memo

"Persistence in the community is facilitated by any factor that reduces the overall rate of population decline during 'lean' periods."

Discussing generalist predator populations, the authors observe that material and energy storage stabilize communities. Predators that rely upon stores during periods lacking in prey survive long enough to prevent prey population explosions, thus averting producer exploitation and system collapse. Generalist predators also switch to alternative prey or depend upon subsidies. One might consider these actions examples of a food web's <u>stress response</u>. This stress response would vary by <u>type</u> (i.e. storage utilization, subsidy utilization, alternate internal source).

Potential Concepts: food web (P: productivity D: low to high; P: dynamics D: ?; P: stress response D: type), subsidies (P: type D: biotic to abiotic; P: frequency D: static to infrequent; P: control D: recipient or donor controlled)

Text Segment	Page 379-382	Type	Memo

"…studies all emphasize the importance of storage, as well as the importance of some generalist predator species..."

The articles final pages reinforce the importance of storage and alternative resource utilization (generalist predators selecting alternative prey) in the presence of wood web productivity variation. Food webs store resources during periods of high productivity in order to buffer low productivity periods – an obvious statement.

In retrospect, the dynamics property seems nebulous. Productivity, stress response and subsidy all have dynamic elements.

Table 146: Summary of potential concepts, properties and dimensions for Sears 2007

Concepts	Properties	Dimensions
Food web	Dynamics	?
	Productivity	Low to high
	Stress response	Type (i.e. storage utilization, subsidy utilization, alternate internal source)
Subsidies	Type	Biotic to abiotic
	Frequency	Static to frequent
	Control	Recipient or donor controlled

Coder	John Reap	Date	4/19/2007
Text Segment	Abstract – para. 5	Type	Memo
Reference	Statzner, B., B. Moss (2004) "Linking ecological function, biodiversity and habitat: a mini-review focusing on older ecological literature." *Basic and Applied Ecology* 5 (2): 97-106.		

"…older ecological literature provides elements for a comparative approach linking ecological function, biodiversity and habitat of large-scale, high-biodiversity systems…"

Ecological function, biodiversity and habitat are three broad concepts that appear early in the authors' paper. The authors also introduce more specific concepts such as ecosystem process, habitat complexity, habitat harshness, habitat extent, organism size, organism longevity. They clearly state their intent to link these concepts using allometric relations. Given the authors' stated intent, some of the more specific concepts might be reclassified as properties as coding proceeds.

Potential Concepts: ecological function, biodiversity, habitat, habitat complexity, habitat harshness, habitat extent, organism size, organism longevity

Text Segment	Paragraph(s): 6-14	Type	Memo

"…a number of variables that the older ecological literature links to biodiversity and among themselves."

The paper's "hypotheses" section elaborates each of the more specific concepts introduced in the first five paragraphs and the abstract. One learns that the authors consider ecological processes to be measures of ecological function. Material flow appears to be a property of ecological process with dimensions such as flow type, rate, and specific rate. This is not terribly surprising; many ecologists discuss the importance of material flows. The authors introduce a plethora of properties for biodiversity. These include species, functional group, trophic level and genetic strain. All of these share the common dimension of number. Size is discussed, but clear properties and dimensions beyond mass and median to max. mass are not present. It is important to note that size influences ecological function. Habitat complexity possesses the patch property which is dimensioned by number of patches.

Potential Concepts: ecological process (P: material flow D: material flow type, D: rate, D: specific rate), biodiversity (P: species D: number; P: functional group D: number; P: trophic level D: number; P: genetic strain D: number), size (P: mass D: min, median and max.), habitat complexity (P: patch D: number of patches)

Text Segment	Paragraph(s): 15-24	Type	Memo

"To link these seven variables, we use the six most reasonable (in our view) relations of the 21 possible pairs and express them in form of proportionalities to power terms, because such variables often scale non-linearly as allometric relations."

The authors present a set of hypotheses relating the previous concepts. It should be noted that these hypotheses are plausible, though not confirmed. While relating biodiversity to habitat harshness, they identify abiotic disturbance as a property of habitat harshness that varies dimensionally from mild to severe and from common to infrequent.

The hypotheses presented in this article are tempting targets for misuse for two reasons. First, they seem to add mathematical precision to ecological ideas that are not fully grounded in experimental data. Second, they possess an air of generality in at least my mind, and while they may very well be general statements in ecology, it is by no means certain that these ideas are applicable beyond the bounds of ecosystems. Pseudo-precision and seeming generality make these hypotheses tempting for non-ecologists wishing to extract guidance from living systems. However, I should not dismiss them out of hand. If literature supports these relationships, it may be interesting to test them in non-biological contexts.

Potential Concepts: habitat harshness (P: abiotic disturbance D: mild to severe, D: common to infrequent)

Table 147: Summary of potential concepts, properties and dimensions for Statzner 2004

Concepts	Properties	Dimensions
Biodiversity	Species	number
	Functional group	number
	Trophic level	number
	Genetic strain	number
Ecological function		
Ecological process	Material flow	Flow type
		Rate
		Specific rate
Habitat		
Habitat complexity	Patch	Number of patches
Habitat harshness	Abiotic disturbance	Mild to severe
		Common to infrequent
Habitat extent		
Organism size	Mass	Min., median and max.
Organism longevity		

Coder	John Reap	Date	3/8/2007
Text Segment	Paragraphs: 2-6	Type	Memo
Reference	Taylor, Steven W., Eoin Fahy and Soumitra S. Ghosh (2003) "Global organellar proteomics." *TRENDS in Biotechnology* 21 (2): 82-88.		

"…characteristic N-terminal sequences [para. 2]…(1) the presence of N-terminal presequences…(2) the level homology to Synechocystis; or (3) lack of homology to yeast."

Admits talk of protein separation techniques and achievements, some seemingly more general terms and ideas recur. One of these ideas is the "terminal sequence" or "presequence," which appears in this context as the "N-terminal sequence." A second recurring idea is that of protein homology. Homology means similarity, but what is similar in this context? Is the structure similar; is the chemical formula similar? Homology does have a specific meaning in chemistry.

> Homology – **3 a**: the relation existing between chemical compounds in a series whose successive members have in composition a regular difference especially of one carbon and two hydrogen atoms CH_2 (Dictionary 1993b)

Perhaps, then, homology refers to the chemical composition and structural similarity between proteins. It seems likely that protein homology and terminal sequence are concepts, but their dimensions are not clear.

Potential Concepts: protein homology, terminal sequence

Text Segment	Paragraph(s): 7	Type	Memo

Sometimes the obvious is not obvious. Protein is a concept. It has properties such as function, structure, and origin, and it may have others. In this article, organelles are discussed as places of protein origin / synthesis; protein's origin varies dimensionally by organelle.

Reading about proteins identified in major cell organelles reminds me that I should review a text on cellular biology. Coding sections about the different organelles might lead to novel insights and concepts.

Table 148: Summary of potential concepts, properties and dimensions for Taylor 2003

Concepts	Properties	Dimensions
Protein homology	?	?
Terminal sequence	?	?
Protein	Function	?
	Structure	?
	Origin	Organelles

Coder	John Reap	Date	7/17/2007
Text Segment	Paragraphs: all	Type	Memo
Reference	Tilman, D., P.B Reich and J.M.H. Knops (2006) "Biodiversity and ecosystem stability in a decadelong grassland experiment." *Nature* 441: 629-632.		

"…greater numbers of plant species led to greater temporal stability of ecosystem annual aboveground plant production."

This statement contains both of this article's primary concepts: biodiversity and ecosystems. Magnitude is a property of biodiversity that varies by number of species and Shannon Index. This article emphasizes the system stability property for ecosystems which varies dimensionally from low to high. It contrasts system stability with species stability, which also varies from low to high. Ecosystem productivity is also discussed in relation to biodiversity, and it varies dimensionally from low to high.

The authors clearly believe that increasing numbers of species – higher biodiversity – leads to higher ecosystem productivity and system stability. However, species stability declines.

Potential Concepts: ecosystem (P: System stability D: low to high; P: species stability D: low to high; P: productivity D: low to high), Biodiversity (P: magnitude D: number of species, Shannon Index)

Table 149: Summary of potential concepts, properties and dimensions for Tilman 2006

Concepts	Properties	Dimensions
Ecosystem	System stability	Low to high
	Species stability	Low to high
	Productivity	Low to high
Biodiversity	Magnitude	Number of species
		Shannon Index

Coder	John Reap	Date	6/27/2007
Text Segment	Paragraphs: 1-4	Type	Memo
Reference	Ulanowicz, Robert E. "Trophic Flow Networks as Indicators of Ecosystem Stress" in *Food Webs Integration of Patterns & Dynamics*. (1996) G.A. Polis and K.O. Winemiller Eds. Chapman & Hall: New York.		

"…on the scale of an ecosystem, we will assume that stress is that which gives rise to an inhibition or reversal of…succession."

The concepts of ecosystem stress and succession dominate the first four paragraphs of Ulanowicz's section. Building upon Odum's foundational work on succession, the author hopes to relate the two by quantifying the qualities of an ecosystem that define its succession level. According to Odum, the qualitative hallmarks of increasing succession level are:

1. Increasing species richness
2. Progressively greater trophic efficiency
3. Richer structure for recycling materials
4. More intense overall activity
5. Greater specialization in trophic interactions

Level appears to be a property of succession, and Odum's qualities of richness, trophic efficiency, recycling structure, activity intensity and interaction specialization provide the dimensions which one would use to at least qualify succession level.

Potential Concepts: ecosystem stress, succession (P: level D: richness, trophic efficiency, recycling structure, activity intensity, interaction specialization)

Text Segment	Paragraphs: 11-end	Type	Memo

"…it is clear from this exercise that that there is at least instrumental and pragmatic value to treating ecosystems as entities whose response to stress can be quantified in concrete ways."

Though taken from the conclusion, the above quoted passage summarizes this paper after the methods section. The author quantifies the dimensions of succession using input-output derived metrics. It is clear that degree is a property of ecosystem stress and that the succession dimensions of richness, trophic efficiency, recycling structure and interaction specialization can serve as its measures. The author adds another dimension, ascendancy. Ascendancy is a metric that combines ecosystem size and organization.

If these concepts connect to an overarching principle, then it would be wise to revisit the metrics used to quantify them. I-O analysis is already known in the environmental community, but a holistic biomimetic approach might reveal a novel application for old I-O metrics and an opportunity to import new ones from ecology.

Potential Concepts: ecosystem stress (P: degree D: richness, trophic efficiency, recycling structure, interaction specialization, ascendancy), succession (P: level D: richness, trophic efficiency, recycling structure, activity intensity, interaction specialization)

Table 150: Summary of potential concepts, properties and dimensions for Ulanowicz 1996

Concepts	Properties	Dimensions
Ecosystem stress	Degree	Richness
		Trophic efficiency
		Recycling structure
		Interaction specialization
		Ascendancy
Succession	Level	Richness
		Trophic efficiency
		Recycling structure
		Interaction specialization
		Activity intensity

Coder	John Reap	Date	7/6/2007
Text Segment	Paragraphs: abstract-12	Type	Memo
Reference	Ulanowicz, Robert E. and L.G. Abarca-Arenas (1997) "An informational synthesis of ecosystem structure and function". *Ecological Modeling* 95: 1-10.		

"…a systems property called ascendancy, the increase of which appears to incorporate many of the changes that characterize the successional process."

Concepts such as succession, trophic flow, compartmental biomass, and Liebig's law dominate the abstract. Much of the paper is devoted to quantifying the level of succession of an ecosystem; this property can be quantified using the metrics average mutual information and ascendancy. The authors cite a work by Odum from 1969 that contains other potential dimensions for the level of succession, but I will not reiterate them here. It is probably worth the trouble to obtain and code Odum's original work. Magnitude seems to be the only trophic flow property of interest in this paper, and it seems reasonable that it varies dimensionally from low to high. Compartmental biomass' only property appears to be amount which varies dimensionally by mass. Liebig's Law is mentioned in this set of paragraphs and appears later in the work, but the authors never provide enough information to expand the idea in the form of properties and dimensions.

Potential Concepts: succession (P: level D: average mutual information, ascendancy), trophic flow (P: magnitude D: low to high), compartmental biomass (P: amount D: mass), Liebig's Law

Text Segment	Paragraphs: 13-18	Type	Memo

"…information is that which causes a change in probability assignment."

Information is a pervasive concept in this paper. Ascendancy and other metrics proposed by the authors rely on formulations from information theory. Interestingly, the only concrete property for information is indeterminancy which one dimensions with the Shannon-Wiener index.

Potential Concepts: succession (P: level D: average mutual information, ascendancy), trophic flow (P: magnitude D: low to high), compartmental biomass (P: amount D: mass), Liebig's Law, information (P: indeterminancy D: Shannon-Wiener Index)

Text Segment	p. 9	Type	Memo

The authors' observation about ascendancy's correlation with successional traits is noteworthy. The fact that ascendancy rises in proportion to these traits lends support to the contention that it is a metric for succession.

Table 151: Summary of potential concepts, properties and dimensions for Ulanowicz 1997

Concepts	Properties	Dimensions
Trophic flow	Magnitude	Low to high
Compartmental biomass	Amount	Mass
Liebig's Law	?	?
Information	Indeterminancy	Shannon-Wiener Index
Succession	Level	Average mutual information
		Ascendancy

Coder	John Reap	Date	3/11/2007
Text Segment	Abstract – para. 3	Type	Memo
Reference	Venterink, H.O., M.J. Wassen, A.W.M. Verkroost and P.C. de Ruiter (2003) "Species Richness-Productivity Patterns Differ Between N-, P- and K-Limited Wetlands" *Ecology* 84 (8): 2191-2199.		

"…evaluated whether the kind of nutrient limitation (N, P or K) may affect species richness-productivity patterns..."

Two interesting concepts appear in the abstract: nutrient or, more generally, material limitation and diversity-productivity relationships. The authors state that nutrient levels and ratios influence plant productivity, plant species richness and the relationship between them. Not surprisingly, they observed that relaxation of material limitations often led to increases in productivity, but interestingly, increased productivity correlated with a decline in species richness.

Now, this reminds me of conventional farming. Farmers achieve high yields by fertilizing, weeding, and using biocides to insure the primacy of a single crop species in a plot. Increased material availability coupled with exclusion of competitors and consumers leads to a productive though simple and minimally diverse plot. If farmers only used fertilizer, weeds and pests would enter, thus increasing the diversity of the plot, but the relationship presented in this article suggests that avoiding fertilizer use could also increase diversity. Is this true? Might this diversity-productivity trade-off apply to fields other than plant biology and farming?

Reading further, I find that a plot of richness vs. productivity generates an inverse parabola. Therefore, richness is maximized at intermediate levels of productivity.

Potential Concepts: material limitation, diversity-productivity relationships

Text Segment	Paragraph(s): 15-25	Type	Memo

"Threatened species only occurred at low-productivity sites."

As the article progresses, ideas introduced in the abstract and introductory paragraphs are reinforced. Diversity-productivity relationships appear multiple times in the text. The authors observe declines in species richness as productivity increases.

"…showed that species richness-productivity patterns are different for plant communities that are growth limited by different nutrients..."

During the discussion of "richness-productivity patterns," the authors provide a property for the material limitation concept. As one would expect, the <u>type</u> of material limitation influences system response. Type varies dimensionally <u>by material</u>. One might expect amount to be a property of material limitation, but it appears that the ratio between particular materials, not total amount, is critical in defining limitation.

It is interesting that the richness-productivity pattern changes with the type of nutrient limitation. I wonder if a kernel of generality can be found in this observation. Different industries appear to capitalize on local and regional ore deposits. Might the pattern of industrialization correspond in some way with the richness-productivity patterns observed for plants? Or, perhaps, they might benefit in some way by following patterns observed for plants?

Potential Concepts: material limitation (P: type D: by material)

Table 152: Summary of potential concepts, properties and dimensions for Venterink 2003

Concepts	Properties	Dimensions
Material limitation	Type	By material
Diversity-productivity relationship	?	?

Coder	John Reap	Date	4/27/2006
Text Segment	Paragraphs 1-6	Type	Memo
Reference	Vermeij, G. J. (2006). "Historical Contingency and the Purported Uniqueness of Evolutionary Innovations." Proceedings of the National Academy of Sciencies 103(6): 1804-1809.		

"…physical and economic principles of emergence, competition, feedback and evolution governing historical change are timeless. Beneath the details of time and place, there are repeated structures and patterns in history."

Four words jump from the page: principles, governing, repeated and patterns. He is clearly stating that there are "principles" that do not merely influence but "govern" historical change. These governing principles lead to "repeated structures and patterns." Now, this is quite powerful stuff. For him, history is billions of years, and over these eons, he is saying that the same sorts of things (patterns and structures) recurred because of these principles.

He names these principles, and it should be noted that two of these definitively depend upon the existence of life, while the other two are, to my knowledge, often associated with life. Are these principles considered the standard ones for biology? Would I be able to open a biology textbook, turn to the first chapter and see definitions of "emergence, competition, feedback and evolution"? Evolution will be there, but what about the others?

When I think of principles, I think of "first principles from engineering" - conservation of mass, Newton's Laws, the laws of thermodynamics, etc. But, are his principles like engineering principles? Can I perform emergence calculations; is there a first law of competition?

Potential concepts: governing principles, emergence, competition, feedback, evolution, functional types

"…history is also profoundly contingent. All of history's events pathways, and participants arise from particular initial conditions or antecedent states and are therefore unique."

Here, he accepts the importance of initial conditions in defining following states, but in the same paragraph he also accepts that the sheer number of possible outcomes makes prediction based on initial conditions hopeless. Contingent is an interesting word. I think of back-up plan when reading it. But, here it seems to mean dependent or conditioned by something else. He quotes authors that clearly see life and its history as contingent in the sense that its development was largely a random accident. Something radically different could have come from the same conditions.

Now, this appears in opposition to his statements about "governing principles." He is actually staging an argument, an argument in which he favors the preeminence of principles. The paper makes an argument for this based upon the fossil record. He does leave a significant role for contingency, but declares, "history predictable at the scale of phenotype, ecological roles and directions of change."

Potential concepts: phenotype, ecological role

Coder	John Reap	Date	4/28/2006
Text Segment	Paragraphs 7-	Type	Memo
Reference	Vermeij, G. J. (2006). "Historical Contingency and the Purported Uniqueness of Evolutionary Innovations." <u>Proceedings of the National Academy of Sciencies</u> 103(6): 1804-1809.		

"…define an evolutionary innovation as a newly evolved structure or condition that enables its phylogenetically derived bearer to perform a new function or that improves…performance…in an…established function."

Here, he starts telling us about the types of things that his principles might cause to happen repeatedly. He lists eyes and mineralized skeletons as examples of repeated "structures," but he does not list any "conditions." Even in his tables of innovations, only "Trees and Secondary Growth" come close to a condition. Are conditions, therefore, rare, or are they hard to identify?

He also defines and starts using an interesting term, "evolutionary innovation." This term is likely a concept, and it has the property of <u>frequency</u> with one dimension ranging from <u>singular to repeating</u>. Innovations that happened more frequently might have been forced by his principles, and therefore, studying them might give me an idea of what the principles happen to be. Apparently, such innovations can happen through "convergent" or "parallel evolution."

He goes on to site and make arguments against the singularity of innovations.

Potential concepts: evolutionary innovation (P: frequency D: singular to repeating), convergent evolution, parallel evolution

"It is striking that many…purportedly unique events in the early history of life result from the union, cooperation, and integration of previously independent components. …early unions…belong to a class of phenomena that have occurred throughout the history of life and that are major sources of innovation."

This is powerful stuff, literally. He states that unions are recurrent and enhance "power and competitive ability." Does he mean power in terms of energy per unit time? Power and competitive ability might be concepts.

Cooperation receives great attention in the paragraphs surrounding this quotation, and he notes its recurrence. He lists multicellularity and eusociality as examples of fundamentally important cooperative arrangements. I know that game theoretic design problem solutions are better when cooperation is allowed. There might be a connection, here. Cooperation among organisms or in living systems might be something worth sampling.

Potential concepts: power, competitive ability, cooperation in living systems

"…innovations…are expected to arise multiple times in many clades…'Whenever suitable energy flow is present, selection from among many energy based choices rewards and nurtures those systems that engender pathways capable of drawing and using power per unit mass up to a point beyond which too much power can destroy a system.'"

The use of innovations figures prominently in this quote, as it does in most of the paper. He again associates the property of frequency with innovation, and he states his beliefs about the recurrence of innovations.

Chaisson's quote relates the concept of power to the concept of selection. This is an important statement because it suggests a biologically derived principle for sustainability (*Life accepts an upper limit on power per unit mass.*). This is truly the type of thing that I am after - relations between big concepts in clear, concise prose with the ring of generality. Some other concepts appear in the quotation such as energy flow which has the property of <u>suitability</u> and dimensions of <u>suitable to unsuitable</u>. It might be insightful to understand how these ideas relate to selection and power. He uses suitable energy flow as a condition for the relationship between selection and power here. How is this determined; what happens to the relationship if it is not in effect?

Potential concepts: energy flow (P: suitability D: suitable to unsuitable)

Table 153: Summary of potential concepts, properties and dimensions for Vermeij 2006

Concepts	Properties	Dimensions
Governing principles		
Emergence		
Competition		
Feedback		
Evolution		
Functional Types		
Phenotype		
Ecological role		
Evolutionary innovation	Frequency	Singular to repeating
Power		
Competitive ability		
Cooperation in Living Systems		
Energy flow	Suitability	Suitable to unsuitable

Coder	John Reap	Date	2/9/2007
Text Segment	Pages 292-295	Type	Memo
Reference	Vermeij, G. J. (2004). Nature: An Economic History. Princeton: Princeton University Press.		

"…economic life on our planet has exhibited a long-term, though occasionally interrupted, trend toward increased power and independence…because prolific resources have made it possible [and] because powerful economic players have helped increase the supply of resources and thus to stimulate production."

In the opening sentences of his final chapter, the author concisely states one of his central themes: life tends toward greater power consumption. As the quote suggests, he believes this trend toward greater power is partially a function of the actions of "economic players." He seems to use a more descriptive term, "controlling agents," for players on page 295. Power and energy are terms that occur in close proximity to these terms. Energy intensity may be a dimension for this concept that varies between powerful and low powered.

After stating his belief that this trend exists, he also states that it is the "…inevitable consequence of first principles." What are these "principles"? He does not state them, but they seem to have something to do with competition, selection and evolution in general. When I think of first principles, I think of Newton's laws or the Laws of Thermodynamics. Are Vermeij's principles similar to those, more familiar ones? Can they be stated mathematically?

The idea of "limits" to growth also appears in this section. He observes that the growth of social, biological and economic entities "…cannot continue without limit…" He cites examples ranging from forests in succession to Europe's Dark Ages as examples of systems that grew toward and stabilized near limits. He believes "supply" and "available technology" create these limits. What is meant by supply? Supply seems to refer to physical resources such as material and energy; in the human context it might also mean money. Supply and technology might be properties of these fundamental limits. One might, therefore, have a (1) supply limit, (2) technology limit or (3) a limit that combines the two. If these are properties, what are their dimensions?

Combining the trend toward greater power with the observation that systems reach and oscillate around limits, one reaches a paradox which Vermeij clearly acknowledges. Do systems grow or stabilize? How can a system both grow and stabilize? The resolution to this conundrum is the introduced idea of "punctuated equilibrium." This idea seems to hold that periods of rapid change will be separated by periods of actual or comparable stability or dynamic equilibrium. The periods of rapid change are triggered by "disruptions" upon which certain "competitors" can capitalize. I think this set of ideas contains a concept – perhaps the growth vs. limit paradox would be a good name, or maybe, it relates to the actions of control agents? The disruptions seem to allow replacement of one "cadre" of control agents with another. Might influence be another property of control agents with dimensions varying from dominant to potential?

Potential concepts: controlling agent (P: energy intensity D: powerful to low powered; P: influence D: dominant to potential), growth limits (P: supply; P: technology)

Table 154: Summary of potential concepts, properties and dimensions for Vermeij 2004 #1

Concepts	Properties	Dimensions
Controlling agent	Energy intensity	Powerful to low powered
	Influence	Dominant to potential
Growth limits	Supply	?
	Technology	?

Coder	John Reap	Date	2/9/2007
Text Segment	Pages 302-	Type	Memo
Reference	Vermeij, G. J. (2004). Nature: An Economic History. Princeton: Princeton University Press.		

"…seven realities about economic systems…[arising]…from first principles and…supported by overwhelming empirical evidence.

1. there is always competition for resources
2. there is always inequality for the parties involved in competitive interactions
3. there is always adaptation by economic units
4. there are always disturbances, some common and mild enough to be incorporated into adaptive hypotheses, others so rare and intense that they disrupt economic systems
5. no adaptation, and no adapted system, is perfect
6. adaptive response is less disruptive when resources are abundant and when the economic system is growing
7. successive economic dominants show a pattern of increasing per capita energy use and power through time and create positive feedback with resources, so that they and the economy they control become more independent of their environment even as they increasingly modify internal conditions."

In this lengthy statement, the author lists seven "realities" arising from "first principles," but in the next paragraph, he seems to refer to these seven realities as principles. This is confusing. Are they principles or corollaries that follow from unnamed first principles? Either way, this is as close as the man comes to succinctly stating the "economic principles" that have been mentioned throughout his book.

These realities do contain a number of potential concepts: adaptive response, disturbance and economic dominant. Disturbance clearly has the properties of intensity and frequency that vary between intense and mild and common and rare. Economic dominants also seem to have properties of energy consumption, control and environmental dependence. Energy consumption would seem to vary between low and high while environmental dependence would vary between independent and dependent. Control could have multiple dimensions. It might be long or short range, centralized or defuse and varying from strong to weak. Adaptive response may require more thought or reconsideration. At the moment, I can only think of one property for it – successfulness. This would obviously vary between successful and unsuccessful, but this dimensional variation seems trite and contrived.

He spends the remainder of the section at no small distance from biology. He attempts to apply his ideas and "realities" to the problem of sustainability writ large. He uses his ideas to attempt to define the type of society that would be both sustainable and consistent with his economic realities.

Potential concepts: disturbance (P: intensity D: intense to mild; P: frequency D: common and rare), economic dominant (P: energy consumption D: high to low; P: control D: short to long range, D: centralized to defuse, D: strong to weak), adaptive response (P: successfulness D: successful to unsuccessful)

"Evolution and economics – different expressions of the same principles that govern life and the emergence of life's organization..."

Here, the author clearly declares his belief that evolution and economics are the same in at least an abstract sense. He also advances the opinion that principles do indeed "govern life."

Potential concepts: …

Table 155: Summary of potential concepts, properties and dimensions for Vermeij 2004 #2

Concepts	Properties	Dimensions
Disturbance	intensity	Intense to mild
	frequency	Common to rare
Economic dominant	Energy consumption	High to low
	Control	Short to long range
		Centralized to defuse
		Strong to weak
Adaptive response	Successfulness	Successful to unsuccessful

Coder	John Reap	Date	6/6/2007
Text Segment	Paragraphs: abstract to end	Type	Memo
Reference	Wagner, T., C. Neinhuis and W. Barthlott (1996) "Wettability and Contaminability of Insect Wings as a Function of Their Surface Sculptures" *Acta Zoologica* 77 (3): 213-225.		

"…wing surfaces of 97 insect species…were examined…to identify the relationships between the wing microstructures, their wettability with water and their behaviour under the influence of contamination."

As is the case for many other articles associated with this group, self-cleaning and microstructures are the major concepts. The authors most thoroughly develop the concept of microstructure with the concept of insect wings. They assign it properties such as geometric pattern and wettability, giving each the respective dimensions of type and contact angle. It should be noted that wettability depends upon geometric pattern which in turn correlates with species.

The surface to body mass index, "SM index," is a concept unique to this paper. Though described as the ratio of wing area to body mass for male and virgin female insects, the authors oddly claim that it is dimensionless. This claim to dimensionless status deserves further investigation. They plot contact angle against it, and they discuss its correlation with cleanliness. Writing the previous few sentences leads me to believe that SM index might be a dimension for another, as yet unstated, concept. It measures the extent of something… Perhaps, it is meant capture an insect's ability to clean itself. The authors do conclude with a section that argues that large winged insects such as butterflies need these features because their appendages are not long enough. Such a measure might also demonstrate the relative importance of wings for a particular insect.

Potential Concepts: self-cleaning, microstructures (P: geometric pattern D: type; P: wettability D: contact angle), SM index [or is this a dimension?]

Table 156: Summary of potential concepts, properties and dimensions Wagner 2006

Concepts	Properties	Dimensions
Self-cleaning	?	?
Microstructures	Geometric	Type
	Wetability	Contact Angle
SM index	?	(See text)

Coder	John Reap	Date	6/15/2007
Text Segment	Paragraphs: abstract-5	Type	Memo
Reference	Williams, P.D., T. Day, Q. Fletcher and L. Rowe (2006) "The shaping of senescence in the wild" in *Trends in Ecology and Evolution* 21 (8):458-463.		

"…classical theories of senescence states that environments posing a high risk of mortality favor the evolution of rapid intrinsic deterioration..."

Senescence is the central concept in this article. Senescence is defined as the process of growing old or the life phase between maturity and death. Deterioration rate is one property of senescence introduced early in the article. It varies dimensionally from low to high, but it also seems to have variation in functional form (i.e. constant, reversing, etc.). Much of the paper focuses on different organism models for senescence. The authors conclude by stating that last word on senescence has not yet been said.

Products wear and deteriorate as a function of factors such as utilization and environmental conditions. A direct relation between product wear and organism senescence is implausible, but combining the idea of senescence with that of ecosystems or food webs might prove insightful. I seem to recall a previous memo that mentions the aging of water bodies. The *senescence-ecosystem* connection might be worth exploring in greater detail.

Potential Concepts: senescence (P: deterioration rate D: low to high, by functional form)

Table 157: Summary of potential concepts, properties and dimensions for Williams 2006

Concepts	Properties	Dimensions
Senescence	Deterioration rate	Low to high
		By functional form

Coder	John Reap	Date	7/7/2007
Text Segment	Paragraphs: abstract	Type	Memo
Reference	Woodward, G., B. Ebenman, M. Emmerson, J.M. Montoya, J.M. Olesen, A. Valido and P.H. Warren (2005) "Body size in ecological networks". *Trends in Ecology and Evolution* 20 (7): 402-409.		

"Body size determines a host of species traits that can affect the structure and dynamics of food webs, and other ecological networks..."

The two major concepts introduced in the abstract are ecological networks and food webs. Food webs are a subset of ecological networks, but given the amount of information already gathered about food webs, I will maintain them as a separate concept. Ecological networks and food webs share the properties of structure, dynamics and stability. Presumably, stability varies dimensionally from low to high. Dimensions for the other two properties are not apparent in the abstract.

Potential Concepts: ecological networks (P: structure D: ?; P: dynamics D: ?; P: stability D: low to high), food webs (P: structure D: ?; P: dynamics D: ?; P: stability D: low to high)

Text Segment	Paragraphs: 1-4	Type	Memo

"Within an ecosystem, species are linked to one another via a network of interspecific interactions..."

The organism interaction concept appears in the first paragraph following the abstract with some of its usual properties: predator-prey and facilitation. The idea of a mutualistic web is also mentioned. The authors state that few mutualistic web studies exist; so, it may be difficult to find enough material to expand this concept.

Stability may be a property of ecological networks, but enough information is presented in these paragraphs to discuss it as an independent concept as well. It has properties of resilience, permanence, resistance and internal perturbation resistance. Resilience describes a system's ability to remain stable by returning to a prior state once disturbed, while resistance describes its ability to maintain structure in the face of a permanent disturbance. Internal perturbation resistance captures the capacity of some stable systems to maintain internally constant conditions. Conceivably, all four vary dimensionally from low to high.

Potential Concepts: ecological networks (P: structure D: ?; P: dynamics D: ?; P: stability D: low to high), food webs (P: structure D: ?; P: dynamics D: ?; P: stability D: low to high), organism interactions (P: predator-prey D:?; P: facilitation D:?), mutualistic web, stability (P: resilience D: low to high; P: permanence D: low to high; P: resistance D: low to high; P: internal perturbation resistance D: low to high)

Text Segment	Paragraphs: 5-end	Type	Memo

"…food webs that contain many species and links can be dynamically stable, if most species interactions are weak..."

This quote clearly adds a property to the food web and organism interaction concepts. Connection strength and strength, respectively, lend something to these concepts not provided by the other properties. Strength for both varies dimensionally from low to high. It is interesting to note that the authors believe strong food web connections can lead to cascade extinctions. This point has been raised in other papers.

While not a focus of this coding exercise, the authors devote this paper to body size. They believe that allometric relations for body mass can serve as empirical relations for many ecological phenomena. The argue that, "…metabolic rate, which scales with body size (and temperature), appears to constrain biological processes…at all levels of organization." If true, the universal specific metabolic rate limit observed by Makarieva and coauthors is even greater import than first thought.

Potential Concepts: ecological networks (P: structure D: ?; P: dynamics D: ?; P: stability D: low to high), food webs (P: structure D: ?; P: dynamics D: ?; P: stability D: low to high; P: connection strength D: low to high), organism interactions (P: predator-prey D:?; P: facilitation D:?; P: strength D: low to high), mutualistic web, stability (P: resilience D: low to high; P: permanence D: low to high; P: resistance D: low to high; P: internal perturbation resistance D: low to high)

Table 158: Summary of potential concepts, properties and dimensions for Woodward 2005

Concepts	Properties	Dimensions
Ecological networks	Structure	?
	Dynamics	?
	Stability	Low to high
Food webs	Structure	?
	Dynamics	?
	Stability	Low to high
	Connection strength	Low to high
Organism interactions	Predator-prey	?
	Facilitation	?
	Strength	Low to high
Mutualistic web	?	?
Stability	Resilience	Low to high
	Permanence	Low to high
	Resistance	Low to high
	Internal perturbation resistance	Low to high
Metabolic rate	?	?

Coder	John Reap	Date	7/27/2007
Text Segment	Paragraphs: abstract - end	Type	Memo
Reference	Worm, B., E.B. Barbier, N. Beaumont, J.E. Duffy, C. Folke, B.S. Halpern, J.B.C. Jackson, H.K. Lotze, F. Micheli, S.R. Palumbi, E. Sala, K.A. Selkoe, J.J. Stachowicz, R. Watson (2006) "Impacts of Biodiversity Loss on Ocean Ecosystem Services." *Science* 314: 203-209.		

"…rates of resource collapse increased and recovery potential, stability, and water quality decreased exponentially with declining diversity."

This article explores the relationship between the concepts of ecosystem and biodiversity from the negative perspective. Instead of discussing the consequences of increasing the later for the former, it explores the result of decreasing biodiversity in ecosystems. The provided quotation reveals a raft of properties ascribed to ecosystems: productivity, stability and purification potential. Later, one finds that the authors add resource consumption and nutrient cycling to this list. All of these properties vary dimensionally from low to high. It should be noted that stability can be divided into resistance to change and recovery from change.

Biodiversity has properties such as magnitude and trophic level. Magnitude can be thought to vary by species richness and functional group while trophic level is classified as either consumer or producer. Most of the metrics are plotted against species richness; so, while functional grouping is mentioned, it is not utilized as a measure in this article.

Higher levels of ecosystem productivity, stability, purification potential, resource consumption and nutrient cycling are associated with larger magnitudes of biodiversity when measured in terms of species richness. Such relationships appear in other articles. This relationship applies for both consumers and producers. Moreover, the opposite relationship also holds. Declines in biodiversity, as measured by species richness, result in lower values for ecosystem properties.

Potential Concepts: ecosystem (P: productivity D: low to high; P: stability D: low to high; P: purification potential D: low to high; P: resource consumption D: low to high; P: nutrient cycling D: low to high), biodiversity (P: magnitude D: species richness, functional group; P: trophic level D: consumer or producer)

Table 159: Summary of potential concepts, properties and dimensions for Worm 2006

Concepts	Properties	Dimensions
Ecosystem	Productivity	Low to high
	Stability	Low to high
	Purification potential	Low to high
	Resource consumption	Low to high
	Nutrient cycling	Low to high
Biodiversity	Magnitude	Species Richness
		Functional group
	Trophic level	Consumer to producer

Coder	John Reap	Date	6/30/2007
Text Segment	Paragraphs: abstract - 3	Type	Memo
Reference	Wright, Justin P. and Clive G. Jones (2006) "The Concept of Organisms as Ecosystem Engineers Ten Years On: Progress, Limitations, and Challenges." *BioScience* 56 (3): 203-209.		

"…many organisms alter physical structure and change chemical reactivity in ways that are independent of their assimilatory or dissimilatory influence."

This quotation defines the ecosystem engineering concept. It contains its influence property and provides chemical reactivity and physical structure changes as two general types of influence. The abstract and opening paragraphs are not particularly rich in other concepts, properties or dimensions.

It is interesting to note that the authors believe the traditionally important concepts in ecology are competition, predation, metabolically associated nutrient flows and metabolically associated energy flows. They seem ready to rank ecosystem engineering in the same class.

Potential Concepts: ecosystem engineer (P: influence D: type), competition, predation, metabolically associated nutrient flows, metabolically associated energy flows

Text Segment	Paragraphs: 12-13	Type	Memo

In these later paragraphs, three interesting concepts emerge in relation to ecosystem engineers. Community assemblages seem to be combinations of interacting organisms. Environmental gradients would presumably be changes in biotic or physical elements of the landscape relative to distance or time. Niche construction appears to relate to the order in which one builds a community of organisms. Though lacking properties and dimensions, these concepts are interesting because they remind me of questions related to industrial eco-park and ecosystem assembly. Can one think of industrial ecological gradients that favor particular assemblages of industries? How would one construct an industrial ecological niche? Can the related biological concepts inform answers to such industrial questions?

Potential Concepts: ecosystem engineer (P: influence D: type), competition, predation, metabolically associated nutrient flows, metabolically associated energy flows, community assemblages, environmental gradients, niche construction

Table 160: Summary of potential concepts, properties and dimensions for Wright 2006

Concepts	Properties	Dimensions
Ecosystem engineer	Influence	Type (i.e. chemical reactivity changes, physical structure changes)
Competition	?	?
Predation	?	?
Metabolically associated nutrient flows	?	?
Metabolically associated energy flows	?	?
Community assemblages	?	?
Environmental gradients	?	?
Niche construction	?	?

Coder	John Reap	Date	6/24/2007
Text Segment	Paragraphs: 1-10	Type	Memo
Reference	Young, Kevin D. (2006) "The Selective Value of Bacterial Shape" *Microbiology and Molecular Biology Reviews* 70 (3): 660-703.		

"…few people care that bacteria have different shapes. Which is a shame, because the bacteria seem to care very much."

The concept shape and its many influences on cell functions are the main topics of this paper. The larger cell concept remains in the background, and one could argue that genes, biochemistry and shape are properties of a cell. However, given shape's importance in this paper, it will be primarily treated as an independent concept.

Potential Concepts: shape, cell (P: genes D: ?; P: biochemistry D: ?; P: shape D: ?)

Text Segment	Paragraphs: 11-p 671	Type	Memo

"…dependence on the laws of diffusion exerts a powerful constraint on cell size and may also influence shape."

Nutrient response appears to be a property of cell shape. The authors measure nutrient response in terms of surface to volume ratio and structure (i.e. filaments, prosthecae). The physical relationship between shape and nutrient response is described by diffusion laws. If this property proves useful, reviewing articles about the influence of diffusion on cells might prove useful.

In their discussion of cell division and growth, the transience (or lack there of) of cell shape is mentioned. They observe that shapes often, though not always, resist change during the life cycle of cells. It seems, then, that transience is a property of shape and that it varies dimensionally from temporary to permanent.

Potential Concepts: shape (P: nutrient response D: surface to volume ratio, structure; P: transience D: temporary to permanent), cell (P: genes D: ?; P: biochemistry D: ?; P: shape D: ?)

Text Segment	p674-675	Type	Memo

"…overall impression is one of directed morphological organization."

Quorum compatibility is another property of shape. The authors state that some shapes are better suited to colony formation than others. Some "anti-social" shapes form gaps in colonies. Interestingly, multiple shapes can coexist in biofilms, suggesting the existence of different functional roles for the different shapes. It is not clear how one would measure quorum compatibility. The author describes anti-social shapes as ones that form gaps in a colony; so, perhaps, one could measure it in terms of the ratio of populated area to colony area.

Potential Concepts: shape (P: nutrient response D: surface to volume ratio, structure; P: transience D: temporary to permanent; P: quorum compatibility D: ?), cell (P: genes D: ?; P: biochemistry D: ?; P: shape D: ?)

Text Segment	p678-682	Type	Memo

"…each appraised the energy demands that motility and chemotaxis impose on bacteria..."

Bacterial motility is an interesting concept with potential environmental bearing on those interested in designing MEMS and NEMS devices. It has properties such as energetics and kinetics. The appropriate dimensions for the energetics property are not clear, though the author provides references that are likely worth a look. Kinetics vary dimensionally by type of motion (i.e. "run and tumble").

Potential Concepts: shape (P: nutrient response D: surface to volume ratio, structure; P: transience D: temporary to permanent; P: quorum compatibility D: ?), cell (P: genes D: ?; P: biochemistry D: ?; P: shape D: ?), bacterial motility (P: energetics D: ?; P: kinetics D: type of motion)

Text Segment	p693-695	Type	Memo

"…bacteria do not live in isolated colonies. Instead, they consort with a variety of microorganisms and surfaces..."

Amongst multiple discussions about shape, the symbiosis concept appears rather unexpectedly. Apparently, cell shape can change when a symbiont interacts with a host organism. For example, the authors mention the conversion of rod shaped bacteria into Y-shaped bacteria. I suppose symbiont adaptation might be a property of symbiosis, but such a statement sounds to imprecise.

These pages provide an interesting set of small-scale symbiosis adaptations that might be worth reviewing in greater detail. Rhizobia-legume symbioses are one of the most studied mutualistic interactions, and therefore, papers about this relationship might enhance my understanding of the principles governing resource exchange relationships.

Potential Concepts: shape (P: nutrient response D: surface to volume ratio, structure; P: transience D: temporary to permanent; P: quorum compatibility D: ?), cell (P: genes D: ?; P: biochemistry D: ?; P: shape D: ?), bacterial motility (P: energetics D: ?; P: kinetics D: type of motion), symbiosis

Table 161: Summary of potential concepts, properties and dimensions for Young 2006

Concepts	Properties	Dimensions
Cell	Genes	?
	Biochemistry	?
	Shape	?
Shape	Nutrient response	Surface to volume ratio
		Structure (i.e. filaments, prosthecae)
	Transience	Temporary to permanent
	Quorum compatibility	?
Bacterial motility	Energetics	?
	Kinetics	Type of motion
Symbiosis	?	?

APPENDIX B

CONCEPTS, PROPERTIES AND DIMENSIONS FROM BIOLOGY AND ECOLOGY CODING

This appendix lists concepts and associated properties and dimensions gleaned from open coding memos. It condenses the information found in the open coding memos into a simple hierarchy of terms.

Lead Author & Year	**Concepts**	**Properties**	**Dimensions**
Axelrod, R. (1981)	Evolution	?	?
	Selection	?	?
	Fitness	Survival	Low to high
		Fecundity	Low to high
	Genetic kinship theory	?	?
	Reciprocation theory	?	?
	Group behavior	Cooperation	Low to high
		Altruism	Low to high
		Competition restraint	Low to high
	Cooperative behavior	Robustness	Low to high
		Stability	Low to high
		Initial Viability	Low to high
			Way of achieving (kinship, high interaction frequency, clustering)
Lead Author & Year	Concepts	Properties	Dimensions
Azaele, S. (2006)	Community	Size	Relative species abundance
		Dynamics	Species turnover distribution
		Persistence	?
	Concepts	Properties	Dimensions
	Classification	Genetic	?
		Feature based	Presence or absence
			Configuration
Bascompte, J. (2007)	Concepts	Properties	Dimensions
	Organism interactions	Strength	Visits
		Symmetry	Index of asymmetry
	Interaction network	Type	Mutualist
		Complexity	Species strength
			Species degree
		Heterogeneity	?
	Biodiversity	?	?
Lead Author & Year	Concepts	Properties	Dimensions

Baum, 2001	Biofouling	Initiating condition	Type (i.e. carbon residue deposition)
	Microfouling	?	?
	Microniches	Size	Micrometers
		Occurrence	Many to few
	Self-Cleaning	Passive	Type (i.e. nanorough surfaces)
		Active	Type (i.e. epidermal desquamation, air-water transition induced boundary layer reduction)
Lead Author & Year	Concepts	Properties	Dimensions
Becks, L. (2005)	Chaotic behavior	Type	Chaotic, limit cycle, equilibrium
			True to deterministic
		Degree	Lyapunov exponents
	Food webs	?	?
	Population dynamics	Forcing factors	Extrinsic
			Intrinsic
	Concepts	Properties	Dimensions
Bell, T. (2005)	Biodiversity	Magnitude	Species richness
			Species composition
	Saturation	?	?
	Ecosystem	Function	Type (i.e. productivity)
Lead Author and Year	Concepts	Properties	Dimensions
Belyea, L.R. (1999)	Assembly rules	Scale	Distance
			Organizational level
	Environmental constraints	Type	?
		Effect	Slight to dominant
		Frequency	Chaotic through periodic to constant
	Niche overlap?		
	R* rule?		
	P* rule?		

Lead Author & Year	Concepts	Properties	Dimensions
Berryman, A.A. (2003)	Malthusian	?	?
	Allee effect	?	?
	Competition	?	?
	Interaction	?	?
	Liebig's Law	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Blanckenhorn, Wolf U. (2000)	Viability	Energetic	Required growth energy, maintenance energy, heat dissipation
		Temporal	Development time
		Agility	?
	Selection	Type	Sexual, viability
Lead Author & Year	Concepts	Properties	Dimensions
Briand, Frederic. (1983)	Food web	Size	Species richness
		Structure	Connectance
	Physical environment	Temporal resource variability	Low to high
		Temporal harshness variability	Low to high
Lead Author & Year	Concepts	Properties	Dimensions
Brown, J. (2004)	Pace of life	Metabolic rate	High to low
		Ecological interactions	Many to few
		Speciation	High to low
		Extinction	High to low
	Ecological patterns	Metabolic rate?	?
	Absence of laws	?	?
	Extended metabolism	?	?
	Concepts	Properties	Dimensions
	Flow	Magnitude	No flow to peek
		Variability	Random, periodic and constant

		Continuity	Continuous to discontinuous
	Flow adaptation	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Cadenasso, M.L. (2004)	Food web	Dynamics	?
		Structure	?
	Boundary	Structure	Amount of constituent elements (i.e. measured in biomass for a forest)
			Morphology of constituent elements
		Function	Type (i.e. nutrient flux control, detritus flux control and organism flux control)
		Composition	Number of species
Lead Author & Year	Concepts	Properties	Dimensions
Cardinale, B.J. (2006)	Trophic group	Biomass stock	Mean log ratio
			Peak log ratio
		Resource depletion	Mean log ratio
			Peak log ratio
	Biodiversity	Magnitude	Number of species
	Ecosystem	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Chapman, Michael J. (1998)	Symbiosis	Partner specificity	One to many species
		Information transfer extent	Chemical signal to gene transfer
		Association period	Temporary to permanent
		Partnership range	Parasitism to co-dependence
	Morphogenesis	?	?
	Cyclical symbiont	?	?
	Symbiogenesis	?	?

Lead Author & Year	Concepts	Properties	Dimensions
Chase, Jonathan M. (2000)	Trophic cascade	Length	?
	Ecosystem	?	?
	Food web	Structure	?
		Complexity	Low to high
Lead Author & Year	Concepts	Properties	Dimensions
Colyvan, Mark (2003)	Kleiber allometry	?	?
	Malthusian growth	Inertia	?
Lead Author & Year	Concepts	Properties	Dimensions
Cousins, S.H. (1996)	Food web	Categories or stocks	?
		Trophic relations	?
	Food chain	Length	Number of trophic levels
	Sink web	?	?
	Available energy	Amount	Body size
	Self-organizing system	System attractor	Type (i.e. top predator)
	Ecosystem trophic module or Photon shed	Extent	Area
			Volume
Lead Author and Year	Concepts	Properties	Dimensions
Crutsinger, G.M. (2006)	Ecosystem	Productivity	Aboveground net primary production
	Biodiversity	Magnitude	Species number
			Number of genotypes
			Rarefied richness
	Community	Structure	Number of species per trophic level
Lead Author & Year	Concepts	Properties	Dimensions
Damuth, John (1981)	Population density	?	?
	Size	?	?
	Metabolism	?	?

	Metabolic constraint	?	?
Lead Author & Year	Concepts	Properties	Dimensions
de Ruiter, Peter C. (1995)	Food web structure	Group number	Few to many
		Interaction frequency	Seldom to often
		Chain length	Short to long
		Interaction strength	Low to high
			By pattern
Lead Author & Year	Concepts	Properties	Dimensions
D'Hont, S. (1998)	Ecosystem	Structure	Carbon flux
		Resilience	Carbon flux recovery rate
	Concepts	Properties	Dimensions
	Genealogical tree	Anatomical relationships	Physical and functional organism features
		Genetic relationships	SSU rRNA
		Structure	?
	Molecular phylogenty	?	?
	Endosymbiont hypothesis	?	?
	Concepts	Properties	Dimensions
	Body shape	Surface area	Low to high
		Diffusion efficiency	Low to high
		Sinking efficiency	Low to high
		Drag	Low to high
		Gradient detection	Low to high
			Type
	Fitness landscape	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Ebenman, B. (2005)	Interdependence	Degree	Few to Many
		Magnitude	Weak to Strong
	Extinction Cascade	Risk	Low to High
		Extent	Limited to Extensive

	Community	Viability	Precarious to Robust
		Structure	Number of links
			Modular to Integrated Arrangement
Lead Author & Year	Concepts	Properties	Dimensions
Emlen, D.J. (2001)	Diversity	Resource allocation	Even to particular
			Simultaneous to sequential
		Resource abundance	Abundant to scarce
	Environmental Influence	Functional cost	High to low
Lead Author & Year	Concepts	Properties	Dimensions
	Ecosystem engineer	Influence	Type (i.e. chemical reactivity changes, physical structure changes)
	Competition	?	?
	Predation	?	?
	Metabolically associated nutrient flows	?	?
	Metabolically associated energy flows	?	?
	Community assemblages	?	?
	Environmental gradients	?	?
	Niche construction	?	?
Lead Author	Concepts	Properties	Dimensions
Hansen, 2005	Self Cleaning	Assistance	None to specific cleaning action
			Type (i.e. water, secretions, grooming, etc.)
	Adhesion	?	?
	Energetic disequilibrium	?	?

	Microstructure	Hierarchy	?
		Roughness	Low to high
		Hydrophobicity	Low to high
		Waxiness	?
	Adhesion vs. self-cleaning tradeoff	?	?
Lead Author	Concepts	Properties	Dimensions
Harold, 2007	Cell	?	?
	Architecture	Spatial organization	Casual agents (spatial markers, vectoral physiology, gradient fields and physical forces)
		Functional coherence	?
		Competitive value	?
		Existence time	Short to long
	Self-organization	Dynamic	?
	Self-assembly	?	?
	Self-construction	?	?
	Emergence	?	?
	Order from order	Spatial	Scale
		Temporal	?
	Template	?	?
	Morphogenetic Field	Generation	External to internal
Lead Author and Year	Concepts	Properties	Dimensions
Hastings, A. (2007)	Ecosystem engineer	Influence	Type
		Type	Autogenic or allogenic
		Duration	Seconds to millions of years
		Spatial extent	Centimeters to thousands of kilometers
	Interspecific interactions	Engineered	?
		Non-engineered	?
	Diversity	?	?
	Food webs	?	?
	Inter-food web	?	?

	exchanges		
	Succession	?	?
	Biogeochemical processes	?	?
Lead Author and Year	Concepts	Properties	Dimensions
Hector, A. (2007)	Ecosystem	Function	Type
			Number
		Redundancy	?
	Biodiversity	Magnitude	Number of species
Lead Author and Year	Concepts	Properties	Dimensions
Herre, E.A. (1999)	Mutualism	Degree	"diffuse and indirect" to integrated
		Stability	?
	Host	?	?
	Symbiont	Diversity	Low to high
	Cost-benefit analysis	?	?
	Hamilton's Rule	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Holling, C.S. (1992)	Critical structuring processes	Periodicity	Short to long
		Geometry	Quanta
	Nested hierarchies	?	?
	Home range	Size	Low to high
		Productivity	Low to high
		Discretization	Grain size
	Sampling grain	Size	Grain size
	Succession	Stage	Exploitation, conservation, release, reorganization
	Ecosystem	Structure	Under or over connected
Lead Author & year	Concepts	Properties	Dimensions

Hooker, Henry D. (1917)	Liebig's Law	?	?
	Compensation	Type	Adaptation, etc.
Lead Author & Year	Concepts	Properties	Dimensions
Hooper, D.U. (2005)	Biodiversity	Genetic	?
		Taxonomic	Number of species
			Relative abundance
			Distribution evenness
		Functional	Fulfilled roles
			Similar to distinct
		Structural	?
	Ecosystem properties	Compartment size	Low to high
		Productivity	Low to high
		Nutrient retention	Low to high
		Stability	Chaotic to constant
	Robustness	?	?
	Species interaction	Competition	Low to high
		Facilitation	Low to high
		Mutualism	Low to high
		Disease	Low to high
		Predation	Low to high
	Dominant species	?	?
	Keystone species	?	?
	Ecological engineers	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Hughes, Terry P. (2000)	Food web	Distortion	Type (harvesting, nutrient input)
			Extent
	Ecosystem function	Biomass production	Low to high
		Resilience	Low to high
	Concepts	Properties	Dimensions
	Macroevolution	Dynamics	Extinction rate
			Origination rate
	Evolutionary modifiers	Physical influence	Type
		Biotic influence	Type (i.e. intrinsic: body size, mobility, metabolic rate,

			physiological tolerance limits, feeding type, and dispersal ability; extrinsic: incumbency, predation and competition)
			Intrinsic or extrinsic
Lead Author and Year	Concepts	Properties	Dimensions
Jones, C.G. (1994)	Ecosystem engineering	Organism type	Autogenic
			Allogenic
		Persistence	Short to long
		Resource flow modulation	Number of flows
			Degree of control
		Intention	Phenotype or accidental
		Control	Type (top down or bottom up)
			Asymmetric or symmetric
	Extended phenotype	?	?
	Organism interactions	?	?
	Concepts	Properties	Dimensions
	Exergy maximization	Thermodynamic gradients	Low to high
		Through-put	Low to high
		Storage	Low to high
Lead Author and Year	Concepts	Properties	Dimensions
A. Kahmen (2005)	Ecosystem	Stability	Low to high
		Evenness	Well-mixed to patchy
	Biodiversity	Magnitude	Exponential Shannon-Wiener Index
	Sampling hypothesis	?	?

Lead Author and Year	Concepts	Properties	Dimensions
Kiessling, W. (2005)	Biodiversity	Magnitude	Species number
	Ecosystem	Stability	Low to high
	Scale	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Kirwan, L. *et al*. (2007)	Diversity	Magnitude	Species number
			Relative abundance
	Ecosystem service	Magnitude	Biomass production
			Yield
		Stability	Degree of invasion resistance
Author & Year	Concepts	Properties	Dimensions
Kitano, H. (2004)	Evolvable system	Robustness	?
		Fragility	General to specific
			Serious to catastrophic
		Performance setback	Low to high
		Resource demand	Low to high
	Therapy	?	?
	Perturbation	Internal	By type, i.e. genetic
		Environmental	By type, i.e. drought, disease
	Scale	Spatial	DNA to organism
	Robustness	Perturbation Response	Return to point attractor, periodic attractor, new attractor or instability
	Co-opted robustness	?	?
	Function maintenance	?	?
	Feedback	Positive	?
		Negative	?
		Integral	?
	Alternative mechanism	Type	Redundancy, overlapping functionality, diversity
	Evolutionary	?	?

	capacitors		
	Phenotypic plasticity	?	?
	Convergent evolution	?	?
	Modularity	Physical	?
		Functional	?
		Spatial	?
		Temporal	?
	Decoupling	?	?
	Bow-tie structure	Conserved core processes	?
		Conserved versatile interfaces	?
		Diverse inputs / outputs	?
Lead Author and Year	Concepts	Properties	Dimensions
Knight, T.M. (2005)	Organism interactions	Type	Predation, mutualism
			Species composition
		Magnitude	Low to high
	Community dynamics	?	?
	Trophic cascade	Magnitude	Low to high
	Food web	?	?
Lead Author and Year	Concepts	Properties	Dimensions
Kormondy, E. (1976).	Energy capture	Efficiency	Low to high
	Assimilation	Efficiency	Low to high
	Respiration loss	?	?
	Net production	Efficiency	Low to high
	Energy transfer	Efficiency	Low to high
		Magnitude	Low to high
		Destination	Number
			Type
Lead Author and Year	Concepts	Properties	Dimensions
Laland, K.N. (1999)	Ecosystem engineer	Type	Autogenic, allogenic artifacts, allogenic habitat

			modifications
	Selection	?	?
	Evolution	Momentum	Low to high
	Control web	?	?
	Concepts	Properties	Dimensions
	Ecological law	Counterfactual invariance	?
		Substrate neutrality	?
		Necessity	?
	Area law	?	?
	Longitudinal species proportionality law	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Leibold, M.A. (2004)	Metacommunities	Size	Number of interacting patches
		Connectivity	Number of links
	Patch	Size	Small to large
		Abiotic features	Type
	Feedback	Signal	Type
			Strength
	Patch-dynamic view	?	?
	Species sorting view	?	?
	Mass effects view	?	?
	Neutral view	?	?
	Diversity	?	?
Lead Author	Concepts	Properties	Dimensions
Lotka, A.J.	Evolution		
	Natural selection		
	Available Energy	Availability	Abundant to Scarce
		Utilization	Full to Unutilized
	Energy Capture	Efficiency	Efficient to Inefficient
	Constraint	Mass	
		Other Constraint	
Lead Author & Year	Concepts	Properties	Dimensions
Maherali,	Ecosystem	Productivity	Low to high

Hafiz (2007)	Diversity	Taxonomic	Species number
		Functional	Number of functions
	Organism interactions	Type	Competition, complementarity
		Magnitude	Low to high
Lead Author and Year	Concepts	Properties	Dimensions
Makarieva, A.M. (2005)	Metabolic Rate	Mass-specific	High to low
		Basal	High to low
		Tissue-specific	Tissue type
		Energy-saving	Regime type (i.e. hibernating)
		Growing	Type (reproduction vs. maturation)
			High to low rate
	Ecological dominance		
	Universal Limits	Specific Metabolic Rate	High to Low
	Natural Selection		
	Concepts	Properties	Dimensions
Marquet, P.A. (2005)	Universality	Invariance	Low to high
	Home range	Size	Low to high
		Resource density	Low to high
	Invariants	?	?
	Ecosystem	Structure	Biomass spectra
	Zero-sum dynamics	?	?
	Concepts	Properties	Dimensions
	Protein	Detection	Low to high
			By method
Lead Author & Year	Concepts	Properties	Dimensions
May, Robert M. (1972)	Networks	Size	Node number
		Interaction	Low to high
		Connectance	Low to high
		Stability	Low to high
	Network equivalence	?	?
	Modularity	?	?

	Concepts	Properties	Dimensions
	Motility	Energy cost	Low to high
		Strategy	Type (run and tumble, run and arc, migratory run and reverse and local run and reverse)
	Life-history strategy	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Montoya, J.M. (2006)	Ecological network	Stability	?
		Resilience	Eigenvalue
		Structure	Complexity
			Clustering
			Connectance
			Linkage strength
			Modularity
		Persistence	?
	Organism interactions	Type	Predation to mutualism
Lead Author & Year	Concepts	Properties	Dimensions
Morris, S. (1998)	Ecosystem	Stability	Number of species
		Resilience	Rate of origination
	Diversity	Fractal structure	Self-similar to dissimilar
Lead Author & Year	Concepts	Properties	Dimensions
Moses, M.E. (2003)	Fertility	Magnitude	Low to high
	Metabolic requirements	Magnitude	Low to high
		Type	Intrinsic or extrinsic
	Energetic network constraint	Scaling	Functional form
		Generality	Specific to universal
Lead Author & Year	Concepts	Properties	Dimensions
Murray, Bertram G. Jr. (2000)	Genotype	Manifestation variation	?
	Phenotype	?	?
	Malthusian parameter	?	?
	Fecundity	?	?

	Survival	?	?
	Evolution	Rate of change	Zero to high
	Selection	?	?
Lead Author and Year	Concepts	Properties	Dimensions
Naeem, S. (2005)	Biodiversity	Magnitude	Species number
	Ecosystem	Function	?
		Stability	Low to high
		Persistence	?
Lead Author	Concepts	Properties	Dimensions
Neinhuis, C. (1997)	Epidermal microstructures	Water-repellency	Low to high contact angle
			Short to long in duration
		Anti-adhesion	Low to high
			Contaminant type
		Roughness	Slight to distinctive cell convexity
			Type of geometry (convex, papillose and hairy)
		Waxiness	Thin to thick
Lead Author & Year	Concepts	Properties	Dimensions
Newell, Sandra Jo (1978)	Life history strategy	Reproductive effort	Low to high
		Reproductive life span	Short to long
		Age of first reproduction	Time
		Degree of parental care	Low to high
		Fecundity	Low to high
	Succession	Reproductive pattern	Type (i.e. constant, synchronous, random)
		Reproductive effort	Low to high
		Energy storage	Low to high
		Offspring production	Number
		Life span	Long to short
	K-strategy	?	?
	r-strategy	?	?

	Reproductive strategy	Reproductive effort	Low to high
Lead Author	Concepts	Properties	Dimensions
Norris, V. (2007)	Hyperstructure	Transience	Equilibrium or nonequilibrium
	Hierarchy	?	?
Lead Author	Concepts	Properties	Dimensions
Nowak, Martin (2006)	Evolution	?	?
	Selection	?	?
	Organism interactions	Type	Competition to cooperation
		Effectiveness	Excluded to dominant (see text)
	Kin selection	Relatedness	Coefficient of relatedness
	Direct reciprocity	Encounter likelihood	Cooperation probability
		Effectiveness	W > c/b
	Indirect reciprocity	?	?
	Network reciprocity	?	?
	Group selection	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Nystrom, M. (2000)	Disturbance	Magnitude	Low to high
		Duration	Short to long
		Frequency	Low to high
		Spatial distribution	Local to global
		Type	By disturbance (i.e. hurricane, global warming, etc.)
	Resilience	Stability domain	Small to large
	Succession	Level	Pioneer to climax
Lead Author & Year	Concepts	Properties	Dimensions
Odum, E. P. (1997)	Carrying capacity	Adjustability	Rigid to adjustable
		Biomass	?
		Number	?
	r-strategist	Reproductive biomass	High to low

		Maintenance biomass	
	K-strategist	Reproductive biomass	High to low
		Maintenance biomass	
	Existence energy	?	?
	Net Energy	?	?
	Energy acquisition strategy	Type	Hunt to collect
Lead Author & Year	Concepts	Properties	Dimensions
Odum, E. P. (1997)	Competition	Intraspecific	Low to high
		Interspecific	Low to high
	Predation	Control	Indirect to direct
	Parasitism	Species specificity	Low to high
	Predation	?	?
	Commensalism	?	?
	Cooperation	?	?
	Energy acquisition strategy	Type	Hunt to collect
Lead Author & Year	Concepts	Properties	Dimensions
Ostfeld, R.S. (2000)	Food web	Composition	By species (i.e. generalist)
	Community dynamics	Control	Type (top-down, bottom-up and competition within a trophic level)
	Production / resource pulse	Periodicity	Periodic to sporadic
Lead Author & Year	Concepts	Properties	Dimensions
Power, Mary E. (1996)	Abundant species	Influence	Type (i.e. productivity, nutrient cycling, species richness,

			etc.)
			Magnitude or community index (CI)
	Keystone species	Influence	Type (i.e. productivity, nutrient cycling, species richness, etc.)
			Magnitude or community index (CI)
	Top-down control	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Quenette, P.Y. (1993)	Evolution	?	?
	Natural selection	?	?
	Contingency	Influence	Low to high
	Dissipative structures	?	?
	Self-organization	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Rainey, P.B. (2000)	Diversity	Generation	Rate
			Mechanism (selection, mutation, genetic drift)
		Maintenance	?
	Competitive exclusion principle	?	?
	Cross-feeding	?	?
	Environmental heterogeneity breeds organism heterogeneity	?	?
Lead Author and Year	Concepts	Properties	Dimensions
Rooney, N. (2006)	Food web	Structure	Type
			Symmetry
		Productivity	Low to high
		Stability	Eigenvalue

			Transient non-equilibrium stability
		Persistence	?
	Biodiversity	?	?
	Energy channel	Productivity	Biomass growth rate
		Turnover	Biomass growth rate : biomass stock ratio
Lead Author and Year	Concepts	Properties	Dimensions
	Node persistence	Connectivity	Few to many
		Infrastructure support	Low to high
Lead Author and Year	Concepts	Properties	Dimensions
Sachs, J.L. (2006)	Feedback	?	?
	mutualism	Benefit	Magnitude (often measured using a "cost:benefit ratio")
			Type
		Dependency	Facultative (useful under some circumstances, though not necessary) to obligate
		Relationship	Byproduct to reciprocity
	Mutualism breakdown	Type	Parasitism to return to autonomy
		Frequency	?
Lead Author & Year	Concepts	Properties	Dimensions
Schoener, Thomas H. (1989)	Population Control	Mechanism	Type (predation, competition and physical disturbance)
		Context	By environment
	Food web	Size	Trophic element
		Connectance	?
		Productivity	Low to high

		Dimensionality	Number of dimensions
		Maximum chain length	Low to high
		Loose-knitness	Low to high
		Vulnerability	Low to high
		Fraction basal species	Low to high
	Concepts	Properties	Dimensions
	Defense reactions	scale	Organizational levels
		motivation	Egoistic to altruistic
	Material removal	Path type	Responsible organism
		Path number	Few to many
		Magnitude	Small to large
	Substance concentration	?	?
	Input resistance	?	?
Lead Author & Year	Concepts	Properties	Dimensions
Sears, A.L.W. (2004)	Food web	Dynamics	?
		Productivity	Low to high
		Stress response	Type (i.e. storage utilization, subsidy utilization, alternate internal source)
	Subsidies	Type	Biotic to abiotic
		Frequency	Static to frequent
		Control	Recipient or donor controlled
	Concepts	Properties	Dimensions
Statzner, B. (2004)	Biodiversity	Species	number
		Functional group	number
		Trophic level	number
		Genetic strain	number
	Ecological function		
	Ecological process	Material flow	Flow type
			Rate
			Specific rate
	Habitat		

	Habitat complexity	Patch	Number of patches
	Habitat harshness	Abiotic disturbance	Mild to severe
			Common to infrequent
	Habitat extent		
	Organism size	Mass	Min., median and max.
	Organism longevity		
	Concepts	Properties	Dimensions
	Protein homology	?	?
	Terminal sequence	?	?
	Protein	Function	?
		Structure	?
		Origin	Organelles
Lead Author and Year	Concepts	Properties	Dimensions
Tilman, D. (2006)	Ecosystem	System stability	Low to high
		Species stability	Low to high
		Productivity	Low to high
	Biodiversity	Magnitude	Number of species
			Shannon Index
Lead Author and Year	Concepts	Properties	Dimensions
Ulanowicz, Robert E. (1996)	Ecosystem stress	Degree	Richness
			Trophic efficiency
			Recycling structure
			Interaction specialization
			Ascendancy
	Succession	Level	Richness
			Trophic efficiency
			Recycling structure
			Interaction specialization
			Activity intensity
Lead Author and Year	Concepts	Properties	Dimensions

Ulanowicz, Robert E. (1997)	Trophic flow	Magnitude	Low to high
	Compartmental biomass	Amount	Mass
	Liebig's Law	?	?
	Information	Indeterminancy	Shannon-Wiener Index
	Succession	Level	Average mutual information
			Ascendancy
Lead Author & Year	Concepts	Properties	Dimensions
Venterink, H.O. (2003)	Material limitation	Type	By material
	Diversity-productivity relationship	?	?
Lead Author and Year	Concepts	Properties	Dimensions
Vermeij, G. J. (2006)	Governing principles		
	Emergence		
	Competition		
	Feedback		
	Evolution		
	Functional Types		
	Phenotype		
	Ecological role		
	Evolutionary innovation	Frequency	Singular to repeating
	Power		
	Competitive ability		
	Cooperation in Living Systems		
	Energy flow	Suitability	Suitable to unsuitable
Lead Author and Year	Concepts	Properties	Dimensions
Vermeij, G. J. (2004)	Controlling agent	Energy intensity	Powerful to low powered
		Influence	Dominant to potential
	Growth limits	Supply	?

		Technology	?
	Concepts	Properties	Dimensions
	Disturbance	intensity	Intense to mild
		frequency	Common to rare
	Economic dominant	Energy consumption	High to low
		Control	Short to long range
			Centralized to defuse
			Strong to weak
	Adaptive response	Successfulness	Successful to unsuccessful
Lead Author & Year	Concepts	Properties	Dimensions
Wagner, 1996	Self-cleaning	?	?
	Microstructures	Geometric	Type
		Wetability	Contact Angle
	SM index	?	(See text)
Lead Author & Year	Concepts	Properties	Dimensions
Warren, P.H (1990)	Food web	Size	Number of species
		Stability	Low to high
	Food web structure	Connectance	Low to high
	Morphological space	Organism anatomy	?
		Behavior	?
Lead Author & Year	Concepts	Properties	Dimensions
Williams, 2006	Senescence	Deterioration rate	Low to high
			By functional form
Lead Author & Year	Concepts	Properties	Dimensions
Woodward, G. (2005)	Ecological networks	Structure	?
		Dynamics	?
		Stability	Low to high
	Food webs	Structure	?
		Dynamics	?
		Stability	Low to high
		Connection strength	Low to high
	Organism interactions	Predator-prey	?
		Facilitation	?
		Strength	Low to high

	Mutualistic web	?	?
	Stability	Resilience	Low to high
		Permanence	Low to high
		Resistance	Low to high
		Internal perturbation resistance	Low to high
	Metabolic rate	?	?
Lead Author and Year	Concepts	Properties	Dimensions
Worm, B. (2006)	Ecosystem	Productivity	Low to high
		Stability	Low to high
		Purification potential	Low to high
		Resource consumption	Low to high
		Nutrient cycling	Low to high
	Biodiversity	Magnitude	Species Richness
			Functional group
		Trophic level	Consumer to producer
Lead Author & Year	Concepts	Properties	Dimensions
Wright, Justin P. (2006)	Ecosystem engineer	Influence	Type (i.e. chemical reactivity changes, physical structure changes)
	Competition	?	?
	Predation	?	?
	Metabolically associated nutrient flows	?	?
	Metabolically associated energy flows	?	?
	Community assemblages	?	?
	Environmental gradients	?	?
	Niche construction	?	?
Lead Author and Year	Concepts	Properties	Dimensions
Young, Kevin	Cell	Genes	?

D. (2006)		Biochemistry	?
		Shape	?
	Shape	Nutrient response	Surface to volume ratio
			Structure (i.e. filaments, prosthecae)
		Transience	Temporary to permanent
		Quorum compatibility	?
	Bacterial motility	Energetics	?
		Kinetics	Type of motion
	Symbiosis	?	?

APPENDIX C

BIOLOGY REVIEW PANEL INFORMATION

This appendix contains information pertaining to the review process undertaken by recruited biology experts. It lists the questions asked of the biology review panel as well as screenshots of the interface used by the panel. Most importantly, this appendix stores their responses to mandatory and optional parts of the questionnaire.

Biology Review Panel Questionnaire

Greetings Biology Review Panel Members:

As part of my dissertation project, I proposed to derive environmental sustainability guidelines or principles for engineering by benchmarking living systems. My goal is to deduce a set of guidelines or principles based on living system principles that can serve as a guiding framework for environmentally benign engineering. Achieving this goal requires completion of three primary tasks:

1) Identification of biological principles

2) Translation of biological principles into engineering guidelines

3) Validation of biological principles and engineering translations

Part of the validation process outlined in my dissertation proposal mandates review of identified biology principles by a panel of biologists. This section of the T-Square website contains six forums presenting and discussing biological principles and initial engineering translations of said principles. (The list of six is not exhaustive; I only claim that the identified six are important.) The process used to extract biological principles from the scientific literature is described in a document attached to this forum (See coding_process_description.pdf). Please, read the extraction process document before reviewing the principles. As members of the Biology Review Panel, you are asked to complete the following tasks.

A. Understand the principle extraction process

A1) Read the extraction process description (coding_process_description.pdf)

B. Answer the following questions about the six biological principles.

B1) Are the presented principles and supporting essays reasonable interpretations of the biological and / or ecological facts and theories? If not, why not, and what is missing?

B2) Are the presented principles and essays excessively biased toward one prevailing interpretation of the biological and / or ecological facts?

B3) In light of your answers to the previous two questions, would you consider the principles to be generally valid biological statements? What caveats and qualifications are needed or would improve the statements?

You are invited, though not required, to comment on the translations. Initial engineering translations have been included to provide context. While all essays presented in the forums are works in progress, this title especially holds for the engineering translations.

Thank You,

John Reap

Screenshots of Online Interface

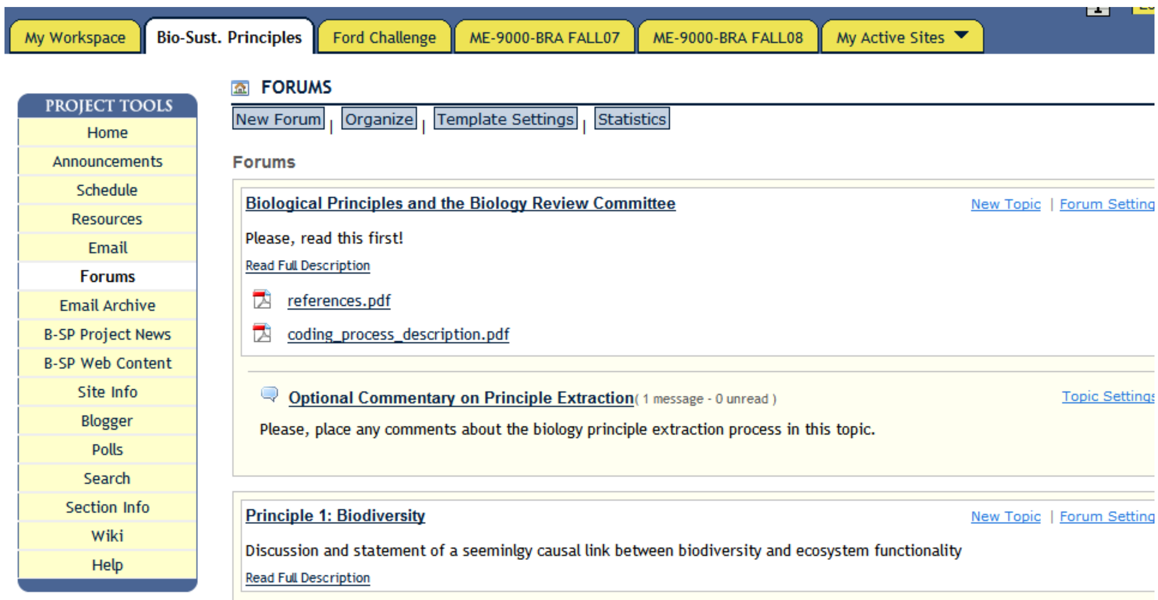


Figure 61: Main review interface

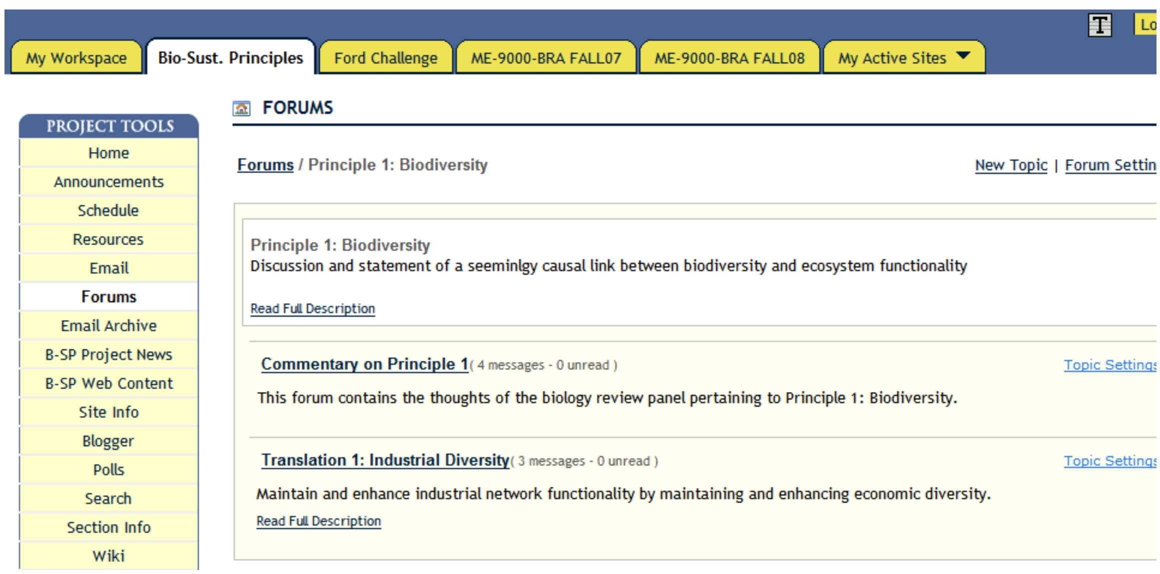


Figure 62: Interface for one biological principle

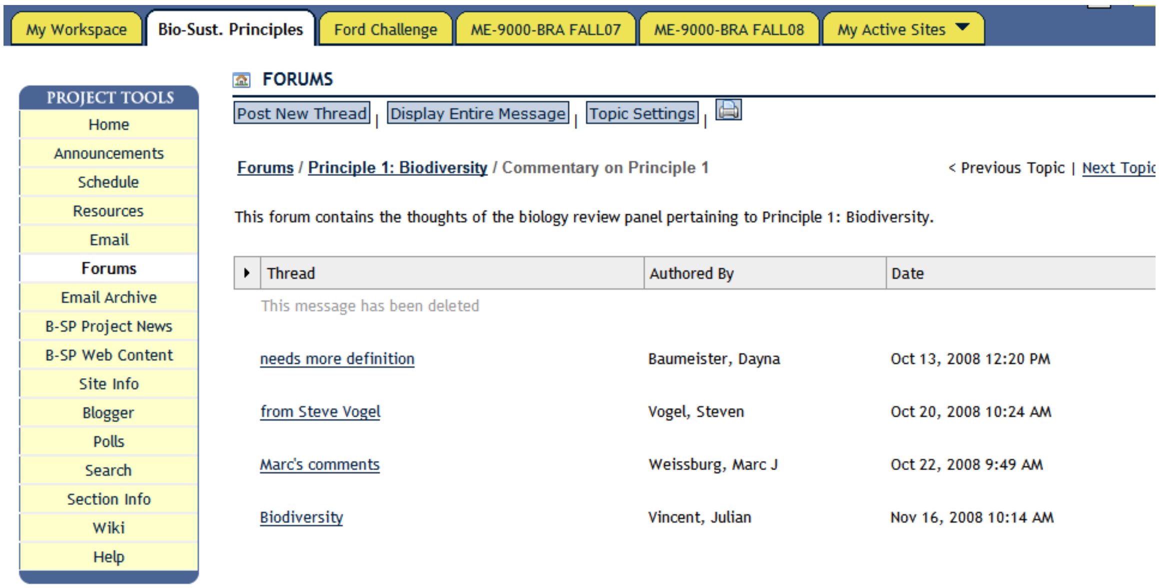


Figure 63: List of comments for a given principle

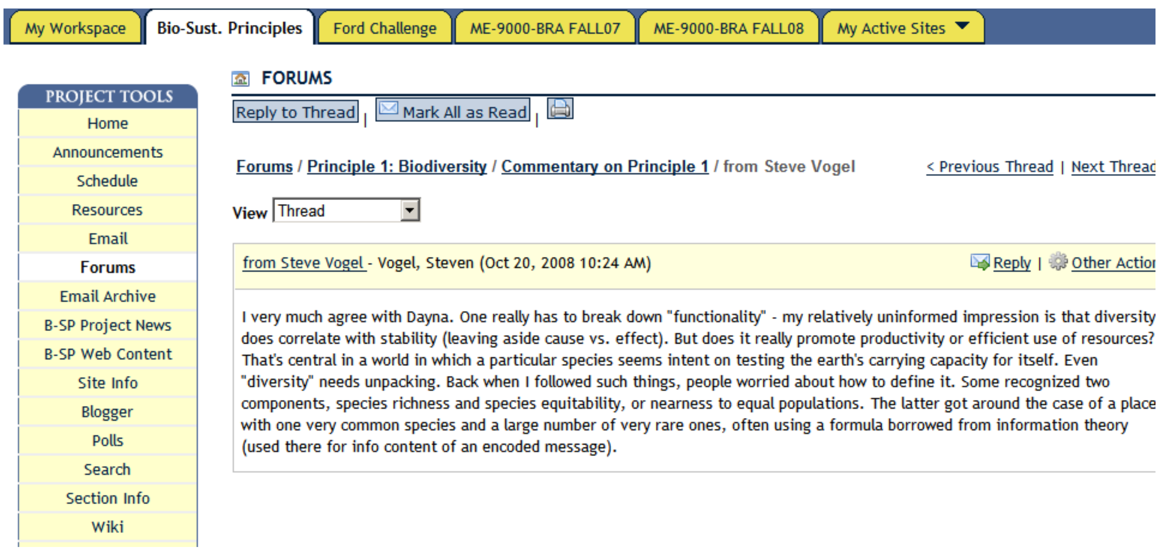


Figure 64: Critique of a biological principle by a reviewer

Reviewer Critiques of Principles and Translations

This section contains critiques of biological principles by members of the biology review panel. It also contains their comments on initial translations of these biological principles into engineering guidelines.

Principle 1: Biodiversity

<u>Dayna Baumeister – needs more definition</u>

I think for this principle to hold true, you need to more specifically define functionality. Biodiversity is clearly measurable, but without defining functionality, you can't measure it and draw the correlation as you have postulated.

It also appears in the literature that diversity plays a role in maintenancy of function as means of resilience. This in turn implies that there is an external context which includes disturbance. Studies in the 90s on peat bogs found that they had very little diversity, yet high stability and ecosystem function. The system, however, had little disturbance.

In short, please define functionality and determine the role of disturbance in the validity of this principle. Which extends to say, is resilience a principle that should be in here?

<u>Steven Vogel – from Steve Vogel</u>

I very much agree with Dayna. One really has to break down "functionality" - my relatively uninformed impression is that diversity does correlate with stability (leaving aside cause vs. effect). But does it really promote productivity or efficient use of resources? That's central in a world in which a particular species seems intent on testing the earth's carrying capacity for itself. Even "diversity" needs unpacking. Back when I followed such things, people worried about how to define it. Some recognized two components, species richness and species equitability, or nearness to equal populations.

The latter got around the case of a place with one very common species and a large number of very rare ones, often using a formula borrowed from information theory (used there for info content of an encoded message).

Marc Weissburg – Marc's Comments

I agree generally with previous comments-let me add some codiciles here.

1) You switch back and forth between several forms of diversity measurements-species diversity, species richness and genetic diversity. On the other hand, you ignore one that may be important, which is functional diversity. Note that "diversity" senu stricto, is not the same as "richness" (which is probably what people think of when they hear the word diversity). Neither is the same as genetic diversity, nor functional diversity. What parts of this do you want to grab hold of? I think the consensus right now is that functional/genetic diversity is more informative, but we often can only measure species.

2) Defining ecosystem function is also important, and not trivial. Many would define this as the rates of material and energy cycling, since that is what ecoystems really do. The proxy for this has often been in terms of the dynamics of portions of the community, since understanding material and energy flow is often very difficult. This is where various terms such as reliance come in. I disagree with Dayna that there has to be an explicit recognition of disturbance in the concept of function-only that disturbance allows us to measure proxies for ecosystem function. This is not to say the concept does not have utility. Other related ideas are resistance and persistance-they are other ways to measure something about ecosystem function.

at the end of the day, much of what you choose to emphasize may be related to your ability to identify analogues for translating these principles. Things for which you cannot define equivalent descriptors or identifiers in human systems, or aspects that are unimportant for human systems, are probably not worth your while to consider.

<u>Julian Vincent - Biodiversity</u>

It seems to me that any organism (system) has a number of functions (performed by its subsystems) which enable it (individual, species . .) to survive. These functions operate within two contexts, which may or may not be separate. These are the genotype and the environment. The effect of environment on genotype leads to the phenotype, and it's the phenotype (which is presumably better 'adapted') which interacts with the environment. Different groups of animals and plants generate different phenotypes, so that the functions are expressed in a variety of ways.

Therefore the components are:

subsystem, which produces single function (e.g. lungs)

system (composed of subsystems) produces a suite of functions which enable the system to survive (an autonomous animal or plant)

Environment (which includes other systems - biotic and edaphic) provides the context within which the functions have to be performed.

Since engineering is a component of animal behaviour, it is inserted into the above scheme at the subsystem or system level, where its function(s) replaces or enhances an existing or otherwise desired function.

This model will generate the complexity found in biodiversity and will also incorporate engineering (technical means of delivering the same or desired functions).

Translation 1: Economic Diversity

<u>Dayna Baumeister - define</u>

Define industrial network functionality.

Why is it economic diversity? Perhaps it should be functional diversity, or niche diversity, or structural diversity....

<u>Steven Vogel – might need a look a literature in economics</u>

Again (as for last principle) I have to reach far back in my education, noting as a caveat the noisiness of what's left in memory. You imply that industrial diversity is a Good Thing. Leaving aside the spatial scale involved, one still has to face a body of economic theory known, if I recall, as the "theory of comparative advantage." It assumes full free-market currencies and economics, cheap transport, no confounding consumer irrationality, etc. What it comes up with is a most efficient system in which each unit (area, nation, etc.) produces just those things it can do more efficiently (with respect to inputs) relative to other units. That says, in effect, that industrial diversity in a given place should be incompatible with efficient use of the local inputs. It argues for specialization, not diversity. Incidentally, the recent award of the Nobel Prize to Krugman recognizes work that puts some real world limits on the applicability of that theory.

<u>Marc Weissburg – Marc's comments</u>

John, this is a good start here, but for it to be useful, I think you need to define function as Dayna mentioned, and importantly, make sure it (or what ever components you emphasize), map on to particular measures of industrial or economic activity. Of equal concern, however, is mapping units of biological organization onto your industrial definitions, and I am not convinced this mapping is accurate. Suppose we think in terms of trophic levels-I see the sequence: extracting-refining-smeltng-production as sort of equivalent to producer-consumer-secondary consumer etc, since prior transformations are required for subsequent ones, and this sequence roughly obeys some of the same basic constraints of trophic systems: energy losses between each steps, energy accumlation in biomass increases (e.g. elton's pyramid of energy). Within that, you may then define species (different niches for, say smelting), and within, or approximately at the same level, something about functional diversity. Your definition of this currently is overly broad-for instance, functional diversity is important within plant groups (e.g N fixers, C3 vs C4), but is subsumed within larger differences such as that occurring between say, producers vs. consumers. My basic point is that biological diversity (or how we think of it) is somewhat heirarchical, and you cannot map one definition (e.g your industrial categories) onto levels arbitrarily and expect this to work.

Principle 2: Ecosystem Engineers

Dayna Baumeister – relatively rare, but still a phenomenon

18 or 36 examples of 30 million potential isn't a very high ratio, but nevertheless, it is clearly documented that as your principle states, organisms can alter the physical conditions of a space and subsequently effect their surroundings. the degree to which they do so varies among species. those that are noted in the cited papers appear to have a disproportionate effect. keystones are noted for having an effect much larger relative to their body mass. Similar to the concept of "invasive species", one could measure qualitiative and quantitatively the characteristics of these engineers that allows them to have the effect that they do (positive or negative). these characteristics might then be drawn parallel to human effects and thereby potentially direct or inform variation in behavior to shifts effects from negative to positive.

i think this is a principle that is worth including. as stated it suggests the organism changes its own physical state rather than its surroundings, so some editing is needed to clarify.

<u>Steven Vogel – or perhaps ubiquitous</u>

I find it hard to imagine a case in which a species that made up an appreciable fraction of the local biomass could not qualify as an ecosystem engineer. Admittedly some species make more difference than others, and admittedly we have (I think) few really good tests involving removal of a particular species to see how a system shifts, either physically or biologically. After all, all living things consume resources, generate outputs, and occupy space. If one takes that view, then the term may not be a useful one - it might be the kind of verbal short-hand that short-circuits proper quantitative evaluation, like (perhaps) "protoplasm" or "metabolism."

<u>Marc Weissburg – either way…not well defined</u>

It seems to me that implicit in the idea of an ecosystem engineer is the notion that it alters things in a unique way-its not, as Steve muses, simply a matter of biomass, and I would try to go back to the literature on this to determine if this can be validated. If I think of ecosystem engineers, I think of coral reefs, elephants, beavers etc-that is organisms that modulate the availability of resources, often creating new niches, and neither would be avialable without this specific organism, e.g. its functional role is not redundant. Now..how to define....Again...it seems to me that without this particular species, material/energy cycling and the organization of the community in terms of its linkages will be quite different. This is certainly true of coral reefs.Again-is this idea present and defensible?

Translation 2: (Ecosystem Engineers)

Steven Vogel – but how to quantify and measure?

I think no ecologist would argue the converse. Thus the biological succession and species diversity increase in a previously bare area has to be similar to, say, industrial/commercial/residential development of some analogous area. Where that similarity takes you must, though, depend on just how one, first, establishes quantitative scales and then obtains data that fit on such scales. I've always figured that nothing is worth measuring unless carefully defined or, put more quantitatively, no measurement, however precise, is better than the precision of the underlying definition of the variable. See, by the way, J. Scott Turner's fairly recent book, "The Extended Organism," for cases in which organisms do things rather close to human engineering. Also, JR and CG Gould's more recent "Animal Architects."

Marc Weissburg – the second problem is connected to the first

..again..unless you have a better way to define ecosystem engineer, you will not be able easily to translate this back. Given the ee seems to affect community structure, this is the logical place to look, and translating this principle to the human domain would then allow some parallel analysis as to whether major transformations in human activity produce changes similar to that of ee's.

Dayna Baumeister – Re: the second problem is connected to the first

I concur with both. As is, there is not quantifiable data, only that the phenomena exists. So what exactly will you be comparing? One could do an assessment of characteristics or principles of ecosystem engineers and those of human engineers and look at the differences, but it would be a rather subjective, qualitative approach. I did my diss on an ecosystem engineer and the focus at the time was trying to understand the mechanism by which ee affect their environment. The list is huge and is not limited to abiotic factors. However, what is interesting about incorporating this principle is the understanding that humans DO alter environments, just as ee do. However, most would agree that the way we alter is markedly different, which begs the question, why, how and should we actually try to emulate ee?

Principle 3: Webs of Life

Steven Vogel – Fine summary - but conclusion?

I cannot fault your reading of the order behind the complexity of ecological systems, that they may look messy, but that reflects complexity rather than randomness. Where I have difficulty is connecting that analysis with the final sentence, a kind of ex cathedra assertion. One assert the same about neural circuitry with perhaps less of a leap of faith, for instance. What kinds of things might we learn and how might we go about extracting the useful lessons? Could the way systems shift in response to perturbations tell us anything? Put another way, has any systems engineer taken a good look at Robert May's simulations, for instance.

Marc Weissburg – systems represent an opportunity that has not been realized

I found this section to be one of the most developed in terms of itd ability to define criterion for assessing function and properties that give rise to the characteristics of biological networks. Engineers have not looked specifically at May, but there are some reports of complex non-biological networks (e.g the internet), which also seem to capture some of the properties of biological networks. Some of these refs are contained in the work of bascompte and colleagues (who are mathematicians,/physicts in fact). I think this validates the final statement that biological networks contain properties of interest (nestedness, scale-freeness, asymetry) that may be generalizable.

Dayna Baumeister – summary is excellent, could pull out multiple principles

Your concluding statement alludes to nutrient/resource/material flows that happen as a result of networks, but much of your discussion is about stability of networks related to ecosystem stability. I would argue that the critical principle in all of this is the very existence of the network, and as Mark has pointed out, its affect on the system as a whole, as well as the individuals. We call it interdependence most simply here and it acknowledges that life (at any scale) does not exist in a vacuum and exactly for that reason, life has leveraged that interdependence. From my understanding, this is quite the opposite in engineering, where most systems are designed with the intent that they should be more or less fully independent. So, this means you will need to further refine your statement to pull out the principle that you most hope to work with.

Translation 3: Weaving Eco-Industrial Webs

<u>Steven Vogel – effective vs. efficient</u>

Again, I think you get the biology just right, and the analogy seems reasonable. What does bother me a bit is the notion of effectiveness as a goal. I'm not sure just what that is except something connected with long-term persistence. It surely does not equate with efficiency, which might be more important for our more-using-less imperative. After all, we can anticipate a future, which natural systems cannot. Thus we should not require that our systems have as much of a self-regulating character, the ability to shift without anticipation. We can go for efficiency as a higher priority. Nature, in effect, resembles a free market, and that tends toward instabilities that complexity (in some analyses) buffers. We ought to be able to do better. see Mokyr, J (1991) Evolutionary biology, technological change, and economic history. Bull. Economic Res. 43: 127-47.

<u>Marc Weissburg – agree and disagree</u>

First read on a complex section. I see the analogies here as being particularly strong. COmercial networks that transform materials and recources can be spoken of in the same language as biological networks as they also transforms material and energy or other resources. Thus, concepts of asymetry, connectedness, etc might be translatable in some form. Where I disagree is that efficiency is a priori, not a consideration of biological networks. To the extent that these networks examine productivity of the system, they examine the overall ability of the system to translate energy input at the basal level to biomass at upper levels, and the amount of material that does not make it into biomass. As energy is generally limiting, unused resources provide an opportunity for some species in the network to exploit them. There is thus an efficiency driver as well as a criterion (at least from the point of view of overall system function)-although the fact that biological networks include a de facto recycling system complicates things somewhat, and I am unsure how to deal with this divergence. I might ask-how strong are the relationships between network structure and efficiency, in terms of primary:secondary production? This data might be hard to come by. As I have previously said, the stabiltity (or lack thereof), in terms of individual species dynamics is often a proxy for overall transformations in a network, since it is easier to track the former than the latter. Suppose we turn the question around: do the abilities of biological networks to resist perturbations in species density and composition translate into efficiency? Is there biological data on this? Are the equivalent analysis in the human domain? When might such an analysis be useful?

<u>Dayna Baumeister – Efficiency is an isolated goal in a complex system</u>

Nature is not optimized for efficiency, although as Mark noted, it does not ignore it either. If the world were not in a state of dynamic, non-equilibrium, the laws of physics would push life towards efficiency (but never at the cost of effectiveness---who cares how efficient you are if you can't pass your genes on). The challenge life faces is that it must also be resilient. In order to have resilience (the ability to maintain function in light of (inevitable) disturbance), organisms and systems use strategies like diversity, decentralization and distribution, and redundancy (an efficient engineers nightmare). The "webs of life" contribute to resiliency and efficiency, which in turn leads to long-term effectiveness. So, given that, I think this is a worthy principle, although it remains vaguely described.

Principle 4: A Metabolic Limit

<u>Steven Vogel – an admirable encapsulation</u>

I'm glad you go with Makarieva et al as primary sources on metabolic scaling. We've heard far too much claptrap from the West-Brown-Enquist crowd (including Gilhooly and some others) who somehow see 3/4 power scaling as a kind of revealed truth that must be pushed with evangelical fervor - to the dismay of every physiologist I know. Why the common upper bounds? My guess is that it mainly reflects the similarity of underlying biochemical processes in all organisms. Thus they all bang up against much the same limit, or, put another way, have to make about the same compromises when dealing with the realities of the other commonality, the same physical world. Our analogs of those biochemical processes are not so fixed, at least temporally speaking. So I don't see why an analogous upper limit ought to apply to our technology. In particular, I think we'd be imposing a possibly counterproductive constraint on technological progress by accepting an analogy.

<u>Marc Weissburg - agreed</u>

‘nuff said.

<u>Dayna Baumeister – agree and disagree</u>

I agree with Steven that the upper bound may indeed be a limit of the common biochemical processes that organisms share. However, arguing that we are immune to those processes, suggests to some degree that we are immune to the laws of natural selection. It could be argued that we don't see organisms beyond that boundary because they were weeded out. Why metabolize? To accomplish needed functions, including the production of artifacts (bones, shells, fur, mounds, etc.) How does this differ than humans need for industrial metabolism? We are merely producing artifacts to meet our human needs. I argue that the way we go about producing these artifacts (energetically speaking) is crossing some sort of historic/evolutionary/geological barrier (or else we wouldn't be in the CO2 mess that we are currently in). So, what does happen if we set an upper limit? Does it promote a series of efficiency measures (isn't that what life has been striving for for billions of years?)? Does it force us to ask is making this thing really metabolically wise? Does it encourage us to look for more innovative and effective energy harvesting systems?

Perhaps the opportunity here lies in looking at the W/kg figures in the making of stuff? (building, growing, etc.) Perhaps it can't be teased out. But, as you can see from the hibernating critters, metabolism does lower when you don't have to "do" anything.

Are there other metabolic correlates other than mass? How does one account for many, many termites creating a large heavy mound? What would a valid "value" actually be?

Maybe the value of this principle is merely noting just how beyond the maximum our metabolism really is.

Translation 4: An Intensive Energy Consumption Limit

<u>Steven Vogel – why limit ourselves?</u>

Again (as in previous post) I don't see nature's example, however well documented and even understood, should be taken as a constraint. What would be fundamentally sinful about, say, an engine that has a power-to-weight ratio greater than anything we now have available? Indeed, one can read the technological history of the last 250 or so years (Newcomen, Watt, and beyond) as a record of progress in increasing the power-to-weight ratios of our engines. First only stationary engines were practical, then railroads, with very low slopes and rolling friction, then steamships with practical levels of fuel efficiency, and on to modern jet engines. Jim Marden has made the argument that engines seem to bump up against a force or stress limit, not an energetic limit, one set by the limitations of the properties of the materials of which they're made.

Marc Weissburg – a different take

I'm not totally convinced the articulation of this principle is the best one either, and I think Steve's question raises an important issue. Indeed, why should we limit ourselves to a certain rate of usage with respect to an individual machine where we have better or different ways of producing or storing energy? Of more interest to me is the scaling issue. Yes, its true that the 3/4 power law is overused, but most biological systems scale to 2/3-3/4 power over an incredibly large range and across many different organisms. Enquist's zeal not withstanding, it seems there is good evidence that this refects some complex constraints associated with transport and/or thermal regulation. The question is whether scaling relationships of the human workd reflect this, and under what conditions. Interestingly, at least one analysis suggests that the "metabolism" of cities (that have a distribution and transportation constraint) also show this 3/4-ish scaling. Perhaps there are some fundamental limits here that would be good to knwo about?

Dayna Baumeister – I concur with mark, and have many reasons why we should limit ourselves

Most of my comments were in the first post, but I think the scaling question does remain and an understanding of what the implications are of such a scale.What does happen when you metabolically scale cities. Industrial ecology is still in the academic realm. What happens when it is applied?

Why limit ourselves? Precisely because we can see that circumglobal transportation is feasible without hauling around a million pounds (yes, that is what a 767 weighs, without fuel) with you. Agreed that our engines have made progress, but what if we were to create a limit that redefined what was possible? Could we make even greater breakthroughs? Surely biomechanics has much to offer in that direction.

Principle 5: The Key to Cleanliness

Steven Vogel – about our best current biomimetic path

I'm purring agreement here. The notion of evolutionary convergence introduced here is, in my opinion, a very powerful tool to see what in nature has functional significance, a way to separate the good wheat from the complex and confusing chaff. After all, natural selection comes down to functional success at the level of the organism - the sine qua non of reproductive success. One further item on superhydrophobicity. Lotus, of course, don't get into adhesion, as do geckos. A bridging application can be found in a recent review by John Bush and David Hu, in the 2006 Annual Rev. Fluid Mech. (38: 339), which looks at insects that walk on water and related systems.

Marc Weissburg – Re: about our best current biomimetic path agreed. comparative analysis and convergence are issues we stress repeatedly in our BID class. In fact, I wonder if this principle can be broadened-organisms use microstructure-nanostructure to control all kinds of interfacial process-in addition to the walking on water, there is also drag reduction and microscale turbulence generation of dolphins and sharks, and vortex shedding in bird wings also seems microstructural. There is also the notion of scale heirarchy here.

Marc Weissburg – ps

insects use the same adhesive attachment mechanism in gecko's-beetles use a mech similar to self-cleaning mechanism in lotus to collect water (again-manipulating surfaces) to adding more fodder to your convergence line of reasoning. Ever wonder why spiders don't stick to their own web? Me too.

Dayna Baumeister – principle is fine, completely different scale than others (not just literally)

Principle stands but it doesn't follow the same rationale for choosing as the others. At this level of specificity, there really isn't any argument. However, as you justify inclusion in the body of your dissertation, you'll need to explain why this is here and not the other numerous examples of convergent evolution.

Translation 5: Surface Suggestions

Steven Vogel – no argument from me

I could not agree more. We're learning a basic lesson about combining surface chemistry and surface microstructure that cannot fail to have useful technological consequences, especially since nano-scale manufacturing has progressed so well in recent years. Now we have to be creative in thinking of applications. I recall comments when lasers first appeared that wondered just what (if much of anything) they could be used for!

Marc Weissburg – why not broaden?

..your focus is on self-cleaning, but that is a lower level particularization of a more general principle-manipulating fluid movement at interfaces. Don't get stuck in this space, if you can avoid it. Why do you think the Lotus-effect effect has 200 patents associated with it? Its all not "cleaning"

Bayna Baumeister – Re: why not broaden?

I like Mark's reasoning, and it opens it up to a level of principle that is at least closer to the others.

Principle 6: Succession

Steven Vogel – nothing succeeds like succession

Succession certainly has come in for lots of attention from ecologists - although interest now seems lower than in the past, as one might infer from the dates of your references. Again, playing curmudgeon, I must wonder whether any gradual transition from simple organization with few players and interactions to complex organization with many players and interactions will share some characteristics. I also wonder if the notion of a "climax community" in the literature on succession really applies either to our economic systems or our technological systems. Both can be affected by quick technological shifts in a way that an evolution-constrained system cannot - except perhaps by immigration of some novel player or by malevolent humans. Finally, I'd note that succession in a given area may not be as deterministic as the old ecologists wanted to believe. A former colleague, John Sutherland, years ago looked at succession on standard ceramic plates placed side by side in an estuary - about as close to fixed conditions as one can get.

Turned out that different plates took different successional trajectories and even arrived at different final stable states. His paper made a lot of folks unhappy.

<u>Marc Weissburg – more darts at the balloon</u>

Steve has alluded to the problems of sucession, and he has hit the nail on the head. Although the gleason vs. the clements debate has powerful appeal-these ideas lack the generality that your analysis conveys. Yes-certain communities do in fact exhibit the progression-but those tend to be the ones that are established in initially harsh environments. Other communities may be halted at specific points by particular species that persist for may years due to their ability to inhibit other potential new colonists. Whether communities fall in to this state is a complex function of very local conditions and luck-and there are multiple and conflicting potential pathways, and perhaps, multiple potential local equilibria. There is also considerable hysteresis, or at least people suspect there is. In other words, a given pathway may exclude other pathways even if the exisiting community is removed. There are quite a few examples of situations in which succession is cyclic and non-equilibrium. In the latter, period disturbance actually results in greatest diversity (and perhaps productivity and efficiency). Different patches exist in different points along this progression, and the nominal, equilibrium point is low diversity, and by implication, possibly less productive. It certainly does not represent a system in which inputs are necessarily efficiently used by the resident organisms, since the functional (as well as taxonimic) diversity is low. There may be some lessons, here, but I am not sure they are the ones you cite. I'd first examine a modern ecology text book for a better read on the state of the field (e.g Krebs, Begon or something similalry process oriented and modern.). I might also look at some of the work by the resilience alliancethey have made some interesting attempts to get some wisdom from these sorts of studies, and offer a fairly balanced, but accessable treatment of community change.

Dayna Baumeister – Re: more darts at the balloon

I agree wholeheartedly with Mark's last sentence of recommendations. I think your summary needs the addition of the latest and then the justification for pulling out the elements that you have in your principle. All systems undergo change and it has a trajectory from simple to complex in the absence of disturbance. The time scale, stalling times, and spatial dynamics are all variables that influence that trajectory, but the systems tends in that direction (although see the super-stable, (at least until recently) bog peatlands of northern canada- they defy the diversity=stability theories). In general, the trajectory vs the characteristics of the ecosystem on the pre-disturbance (as opposed to post-disturbance end) are two very different principles to understand and you'll need to decide which has more value here. The latter overlaps with your food web principle, the former may be very difficult to quantify, but more importantly you'll need to understand the value of that principle as it relates to engineering.

Translation 6: Setting the Direction for Environmental Progress

<u>Steven Vogel – productivity and efficiency</u>

I have serious reservations about this kind of thinking. Sure, specialization tends to lead to greater efficiency in many contexts - but surely not all. Consider one in which transportation costs are high, such as for land transport in the eastern US in 1750. Local self-sufficiency with low specialization rather than "comparative advantage" (described in an early post) and high specialization should have been the effective route. The whole issue of efficiency bothers me as well. Natural selection and efficiency seem only indirectly connected, that is, quite often selection may prefer efficiency (assuming it can be rigorously defined, for the sake of argument), but one can easily point to situations where it takes a back seat. In addition, one needs to look at productivity or some analog of it as well as efficiency. The two have only a distant relationship. (1) For engines, efficiency is fuel consumption vs. power output; productivity might be taken as power-to-weight. These certainly don't run in parallel. (2) For ecosystems, maximum productivity may occur well before a steady-state climax community appears. Thus in the SE US Piedmont, the productivity of the loblolly pine subclimax is higher than that of the final hardwood climax. Admittedly standing crop is higher at climax, but standing crop and productivity cannot be asserted proportional to each other. Finally, I'm bothered, as always, by tacit or explicit arguments that begin with nature as definitional of the right way for things to be done. My counterarguments would take too much space here. I might just put in a skeptical note about how the way nature recycles might just reflect her reliance on enzymatic reactions. What one enzyme can make, another (or, occasionally since these are ultimately reversable reactions, the same enzyme) can unmake. Perhaps she cannot do otherwise than recycle--wastes are automatically put in a bin labelled "stuff for some enterprising organism to consume."

Marc Weissburg – some complications here

I'm not really sure these are reasonable translations. As I mentioned, I think the generality of the successional principles has been overstated. Succession is not a straight arrow that leads to increasing productivity or efficiency. Even in the systems that approximate a Gleasonian ideal, productivity tends to decrease at the latest stages as a result of increasing stress and competion. This causes organisms to invest in tissue that allows toleration of stress, and increases competative ability without leading to more production. Productivity declines, and in particular, the ratio of productivity to bionass (a sort of proxy for efficiency) tends to decrease at the basal level. Production is also rendered inaccessable to many higher trophic levels decreasing energy flow (that's why we end up with coal and oil!). Although this is not always true, it is true often enough. I think the most important lessons from succession may be how to handle a dynamically stable, rather than statically stable system. I think you are thinking alot about the latter, and it may be better to think about the former. Secondly, given different successional modes, and organisms that are adapted to them ,what might this tell us about how to organize industrial activity or commerce?

tada-weissburg crosses the finish line, bested (yet again), by the vogelizer.

<u>Dayna Baumeister – principle as stated in [sic] laden with assumptions that don't follow from summary</u>

Your work and your summaries were extremely well-done. The extraction of the biological principle at the end did not always follow and then was further morphed without the necessary rigor into the translation principle. It seems to me that there is an intention in the extraction process and choice of principles that is important here, namely the WHY? For example, why do systems go through some sort of successional process? What advantages and disadvantages does that imply? You could do this with all of your principles and summaries to then best understand what is the "operating?" principle that follows and hence why engineers might want to emulate that principle.

Give me a call John and we can talk about next steps.

APPENDIX D

THEORETICAL MEMOS FOR CODED BIOLOGY AND ECOLOGY LITERATURE

Theoretical memos, as defined by Constant Comparative Method, are cataloged in this appendix. Each represents an effort to organize or synthesize information extracted from open coding memos.

Coder	John Reap	Date	1/15/2008
Type	Theoretical Memo		
Category	Biodiversity		
Title	Reflections on Concepts and Properties Related to Biodiversity		

Three similar concepts contribute to the formation of the biodiversity category: biodiversity, diversity and diversity-productivity relationship (See Figure 65). To a large extent, properties associated with biodiversity and diversity overlap. The listed properties reveal that biological science has been interested in delineating types (genetic, functional, trophic, etc.) and amounts (or magnitudes) of biodiversity. Diversity-productivity relationship (DPR) lacks properties, but importantly, it describes a different aspect of this category. Its existence reveals that biology also investigates biodiversity's purpose and the consequences of changing its different forms. I recall that similar ideas appear in memos associated with the concepts diversity and biodiversity, but I will need to consult the individual memos for the details.

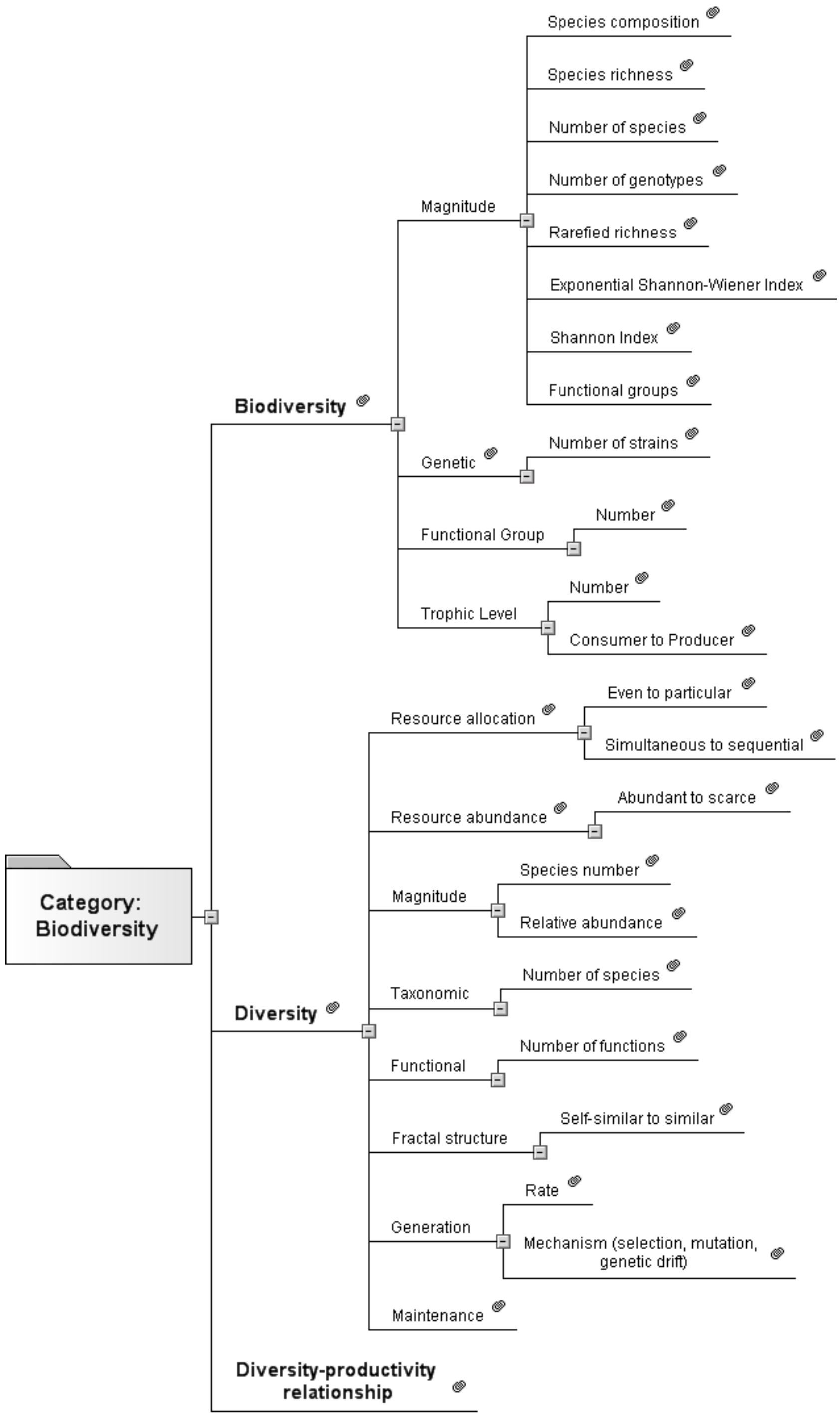


Figure 65: Biodiversity Category with Properties and Dimensions

Properties and dimensions for diversity and biodiversity contain a number of potential metrics for the, as of yet, undefined biodiversity principle. The current list of properties does overlap and can be condensed, though. Many properties refer to types of biodiversity.

Table 162: Types of Biodiversity

Taxonomic	Functional	Fractal Structure
Genetic	Trophic	

A few properties describe biodiversity regulation. These properties were labeled generation and maintenance during coding. A couple others provide information about the resource condition and allocation scheme prevailing during diversification. Turning to the dimension level, the measures and metrics used to quantify each of these represent potential metrics for a biodiversity principle. Some may also serve as variables in experiments designed to test hypotheses about biodiversity's influence on various system functions. Table 162 lists the dimensions for the condensed set of properties.

Table 163: Condensed Properties with Dimensions

#	Property	Dimension
1	Fractal Structure	Self-similar to similar
2	Functional	Functional groups
		Number of functions
3	Generation	Rate
		Mechanism (selection, mutation, genetic drift)
4	Genetic	Number of genotypes
		Number of strains
5	Maintenance	
6	Resource Abundance	Abundant to scarce
7	Resource Allocation	Even to particular
		Sequential to simultaneous
8	Taxonomic	Species number
		Species richness
		Rarefied richness
		Exponential Shannon-Wiener Index
		Shannon Index
		Species composition
9	Trophic	Number
		Consumer to producer

On further reflection, it occurs to me that the information in Table 163 is only valuable if one can identify one or more relationships that might correlate with metrics based on the listed dimensions. I believe a review of the existing memos with an eye for unearthing these relationships is in order.

Coder	John Reap	Date	3/4/2008
Type	Theoretical Memo		
Category	Biodiversity		
Title	Biodiversity Metrics		

This theoretical memo catalogs metrics for biodiversity encountered during open coding. As a starting point, it takes the properties and dimensions of biodiversity reorganized in the first theoretical memo (Biodiv_theoretical_1.memo) on this topic. Table 163 contains these properties and dimensions.

Table 164: Condensed Properties with Dimensions

#	Property	Dimension
1	Fractal Structure	Self-similar to similar
2	Functional	Functional groups
		Number of functions
3	Generation	Rate
		Mechanism (selection, mutation, genetic drift)
4	Genetic	Number of genotypes
		Number of strains
5	Maintenance	
6	Resource Abundance	Abundant to scarce
7	Resource Allocation	Even to particular
		Sequential to simultaneous
8	Taxonomic	Species number
		Species richness
		Rarefied richness
		Exponential Shannon-Wiener Index
		Shannon Index
		Species composition
9	Trophic	Number
		Consumer to producer

Fractal structure refers to periodicity in the fluctuation of extant species caused by extinction events (Sole, et al. 1997). The Fast Fourier Transform metric used to calculate similarity reveals a certain pattern observed in other systems. This pattern, power-law decay, sometimes indicates the existence of self-organizing criticality. It does not directly communicate anything about diversity, and its calculation is somewhat complex. So, for now, it will not be explored any further.

The Functional property possesses two dimensions: functional groups and number of functions. The term functional group refers to a number of organisms sharing an ecologically significant trait. Researchers typically select important traits as part of their study design. They might include leaf nitrogen content, phosphorous uptake, filtering / recycling activity or primary production (Petchey, et al. 2002, Bell 2007). A researcher then assigns sampled species to each functional group. One should note that different members of the same species may serve different functions and that any one organism may fulfill multiple functional roles. For instance, Bell assigned organisms to functional groups based on morphology not taxonomic classification in his reef study, and 100% of the sampled organisms fulfilled the filtering / recycling function (Bell 2007). Number of functions refers to the number of individual functions occurring in an ecosystem. In practice, it likely refers to the number of functions identified for a study. It is, therefore, a suspect measure, being subject to the arbitrary bounds set on a study by a researcher.

According to the memo containing the generation property, its dimensions are implicit. A formula or other method of quantitative estimation does not appear in the attendant paper (Rainey, et al. 2000). The rate of diversity generation would seem to involve the appearance of genetic differences, species or even functional groups per unit time. Examples of the mechanism dimension appear in Rainey's paper. They include selection, mutation and genetic drift; so, characterization of diversity generation using the mechanism dimension simply reduces to listing the ways in which it occurs.

Genetic variation is dimensioned by number of strains and genotypes in the coded literature. The article containing genetic strain merely states that one might measure biodiversity in this way, but it does not clearly define a genetic strain or provide quantification (Statzner, et al. 2004). Genotype is defined as the, “genetic constitution of an organism, usually in respect to one gene or a few genes relevant in a particular context” (Parker 1994). Given the context for genetic strain and genotype’s definition, they seem synonymous. Variations in one or a few genes would readily be regarded as different genetic strains. Ways of quantifying genetic differences must exist; I will search for them later.

Biodiversity metrics related to taxonomic information commonly appear in biology literature. The simplest measure of biodiversity is species number, also known as richness (Purvis, et al. 2000). One may also use other levels of biology’s hierarchical classification scheme such as genius, family, order, etc. (See Figure 19).

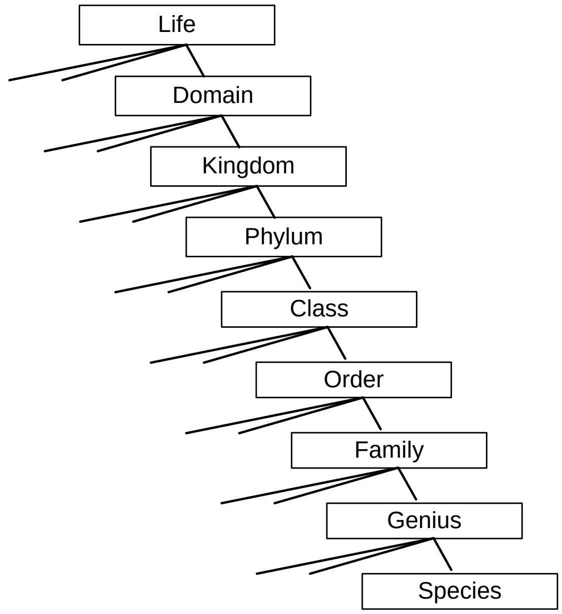


Figure 66: Biological Classification of Organisms

Rarefied richness also measures species number, but the sampling technique differs (Crutsinger, et al. 2006). Instead of simply counting species at a site, one averages small samples repeatedly drawn from a site at random (Gotelli, et al. 2001). Legendre presents a more precise rarefaction formula (Legendre, et al. 1998). He also provides a concise discussion of other species based diversity indices found in the coded biology literature (Legendre, et al. 1998, Kahmen, et al. 2005, Tilman, et al. 2006). Popular diversity metrics include the first three entropy orders and their corresponding diversity numbers which are special cases of the generalized entropy formula (H_a) (Legendre, et al. 1998).

$$H_a = \frac{1}{1-a} \log \sum_{i=1}^{q} p_i^a$$

In the general entropy formula, a = 0, 1, … and determines order. The variable q represents the number of species while p_i is the proportion of species i. The base of the logarithm in the generalized entropy formula is generic and must be specified during use. Species number (N_a) is simply the appropriate exponential of entropy.

$$N_a = e^{H_a}$$

The first three orders (a = 0, 1, 2) and associated diversity numbers follow (Legendre, et al. 1998).

$H_0 = \log(q)$	$N_0 = e^{\log(q)} = q$
$H_1 = -\sum p_i \log(p_i) = H$	$N_1 = e^H$
$H_2 = -\log \sum p_i^2 = -\log(concentration)$	$N_2 = concentration^{-1}$

One should note that first order diversity (a = 0) is sensitive to rare species while third order diversity (a = 2) is sensitive to small changes in the abundance of dominant species. One final approach to measuring taxonomic diversity consists of determining species composition by counting types of species (n_T) in a habitat.

Trophic diversity depends on the number and type of trophic levels. Type describes the general life styles of an organism: producer, consumer, detrivore, etc. Number counts the levels of consumption above primary producer. In an ecosystem where cows eat grass and wolves eat cows, the grass would be a producer (P) while cows and wolves are first (C1) and second level consumers (C2), respectively.

#	Property	Dimension	Metric Description
1	Fractal Structure	Self-similar to similar	NA
2	Functional	Functional groups	Individual organisms or groups of organisms are assigned to predefined categories based on one or more physical activities. Membership in multiple categories is possible.
		Number of functions	Count of functions present in an ecosystem or defined in a study
3	Generation	Rate	Appearance of genetic diff.,

			species or functional groups per unit time
		Mechanism (selection, mutation, genetic drift)	Listing of ways in which generation occurs
4	Genetic	Number of genotypes	
		Number of strains	
5	Maintenance		?
6	Resource Abundance	Abundant to scarce	
7	Resource Allocation	Even to particular	
		Sequential to simultaneous	
8	Taxonomic	Species number	Number of species in a site, habitat or clade
		Species richness	(Same as species number)
		Rarefied richness	Number of species at a site based on an average of randomized samples drawn without replacement
		Exponential Shannon-Wiener Index	$H_1 = -\sum p_i \log(p_i)$
		Shannon Index	?
		Species composition	Types of species, n_T
9	Trophic	Number	Number of levels of consumption (i.e. grass eaten by cow eaten by wolf)
		Consumer to producer	Qualitative classification by way in which organism obtains sustenance – producer, consumer, detrivore, etc.

Coder	John Reap	Date	1/22/2008
Type	Theoretical Memo		
Category	Competition		
Title	Competition – A Dead End?		

Based on my background knowledge of biology, I know that competition of various kinds is an important force that shapes the living world. Organisms compete for: prey, territories, mating opportunities, etc. The concepts in the competition category capture these specific instances of competition in more abstract terms (See Figure 65).

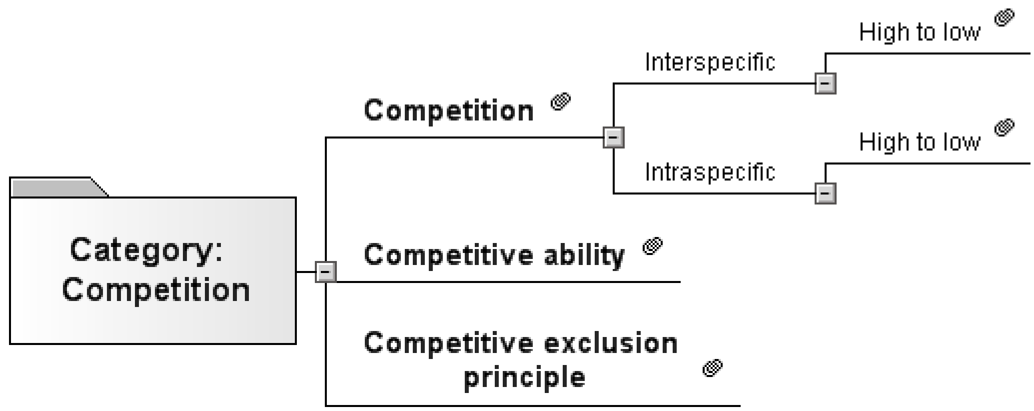


Figure 67: Competition Category with Properties and Dimensions

One sees that competition occurs within and between species. Competitive ability is variable, and such differences can lead to the exclusion of one or more species from a habitat.

Unfortunately, my sample of biology literature does not seem to provide any new insights about competition. Exclusion, differences in competitive ability and the presence of multiple forms of competition are known and studied beyond the bounds of biology. Tomes of work on such topics must exist in economics, and therefore, I doubt that my time would best be spent rediscovering fundamental economic notions. The Competition Category appears to be a dead end.

Coder	John Reap	Date	1/24/2008
Type	Theoretical Memo		
Category	Ecosystem Engineers		
Title	Pruning the Tree and Weaving a Screen		

The two concepts which compose the Ecosystem Engineer Category divide it into one dealing with the engineers and their works of engineering (See Figure 65). The sampled literature more thoroughly discusses the properties that describe the works of ecosystem engineers, though axial coding for particular ecosystem engineers would likely change this. A quick review of the properties assigned to the ecosystem engineering concept reveals some redundancy and one property that should be assigned to the ecological engineers' concept.

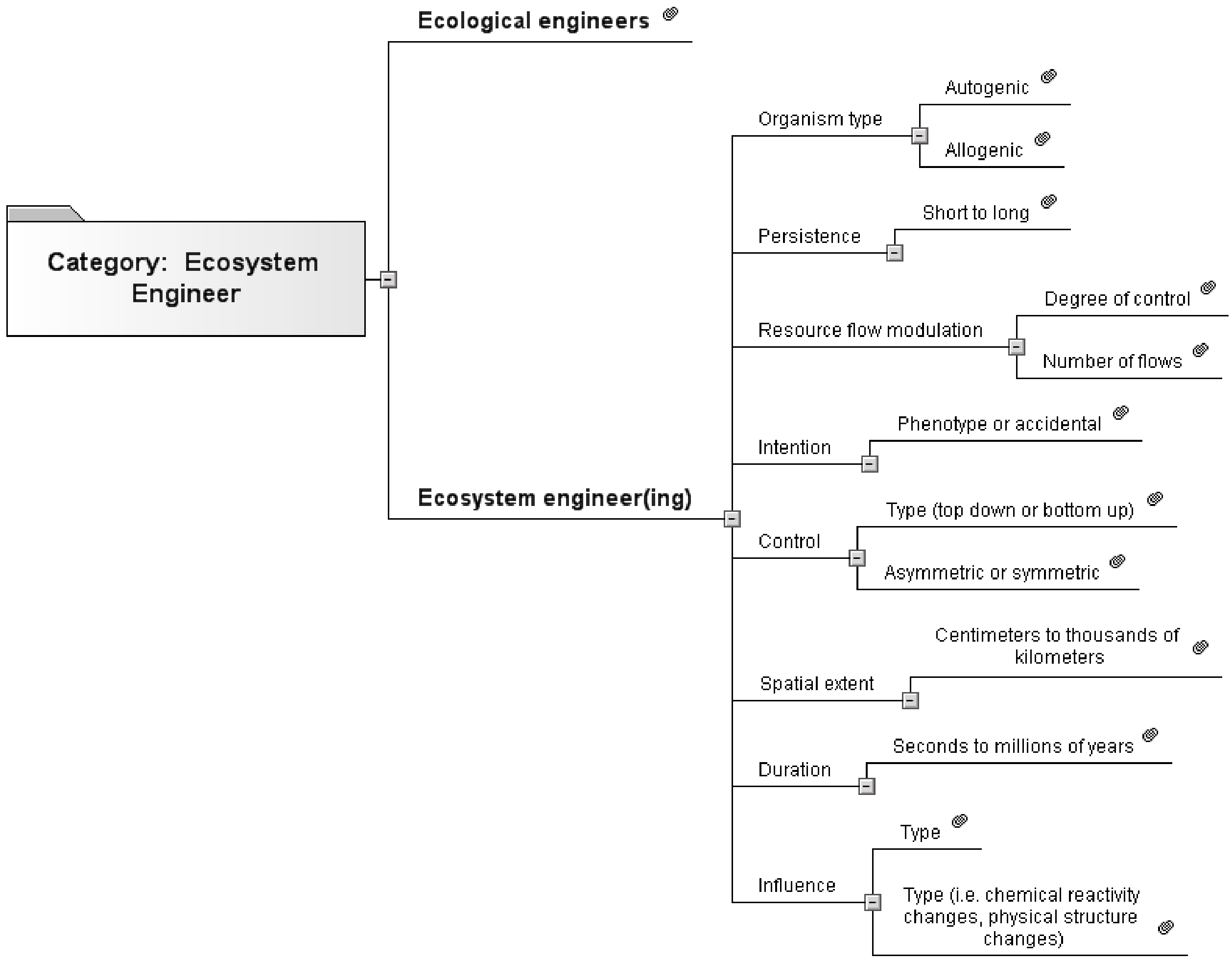


Figure 68: Ecosystem Engineers Category with Properties and Dimensions

Duration and persistence carry the same meaning and should be combined. The improperly assigned property, organism type, likely found its way into the ecosystem engineering list because it also applies to ecosystem engineers, an apparently more common synonym for ecological engineers. Table 165 contains a reorganized and condensed version of the concepts properties and dimensions in Figure 65.

Table 165: Reorganized concepts, properties and dimensions for the Ecosystem Engineers Category

Concept	Property	Dimension
Ecosystem Engineer / Ecological Engineer	Organism type	Autogenic
		Allogenic
Ecosystem Engineering	Control	Type (top-down or bottom-up)
		Symmetric or asymmetric
	Duration	Short to long
		Seconds to millions of years
	Influence	Type
		Type (i.e. chemical reactivity changes, physical structure changes)
	Intention	Phenotype of accidental
	Resource flow modulation	Degree of control
		Number of flows
	Spatial extent	Centimeters to thousands of kilometers

Organisms engineer their environments in multiple ways and seem to utilize the full range of dimensions in Table 165. Some organisms accidentally cause short term changes to local environments that ultimately exert little influence over resource flows while others such as coral reefs display exactly the opposite traits. This fact makes it difficult to identify any one guiding principle in the coded material. What, then, can one learn about environmental sustainability by reviewing coded material?

Conceivably, one might use knowledge gained to categorize engineering activities by expected level of environmental impact. Positions on dimensional ranges for properties such as spatial extent, duration and resource flow modulation indicate the extent of an ecosystem engineer's impact. Other properties reveal the means by which engineers affect changes. Comparing technical activities with those of ecosystem engineers using the same dimensions might provide insight into the magnitude of expected impact. As mentioned, some ecosystem engineers cause large scale, long term changes to their environments. Technical engineering activities possessing similar dimensional positions could be identified as potentially high impact actions. Such a screening technique might aid in identifying projects requiring greater scrutiny, thus allowing a more efficient use of analytical resources.

Coder	John Reap	Date	2/18/2008
Type	Theoretical Memo		
Category	Ecosystem Engineers		
Title	Classifying Ecosystem Engineers		

This theoretical memo classifies ecosystem engineers according to properties and dimensions summarized in the first theoretical memo (ecosystem_eng_theoretical_1.memo) about the ecosystem engineering category. It represents the beginning of an effort to build a screening method meant to identify high impact engineering activities. By associating high impact ecosystem engineers with particular ends of the previously identified dimensional ranges it is hoped that a general pattern for high impact activities will emerge. Such a pattern might provide a means of quickly classifying technical projects with potentially high environmental impacts.

Reviewing the coded articles led to the creation of Table 166. It describes the major dimensional ranges for a majority of the species mentioned in the most prominent papers dealing with ecological engineers (Jones, et al. 1994, Laland, et al. 1999, Hastings, et al. 2007). Notable findings include the:

- Limited number of modulated resource flows,
- Preponderance of changes to land and sea surface geometry and
- Lack of data for some categories.

Resource flows influenced by ecosystem engineers usually fall into the categories of light, water, nutrients or organic compounds. Often, the engineer modulates these flows by changing surface, subsurface or sea floor geometry. The spatial and temporal scales associated with these modulations vary considerably. Multiple microorganisms appear in the table next to large creatures such as whales and trees. Bubble nets last mere minutes while reef mounds may persist for hundreds of millions of years. Unfortunately, dimensions dealing with control and evolution receive scant coverage in available references; so, one cannot elucidate related patterns.

Not surprisingly, the large, persistent engineering works appear to cause the most impact at first glance. It may, however, prove informative to more carefully examine organisms that engineer by changing chemical processes in soil, water and air. I recall that moderately sized (few meters) colonies of organisms contributed to shifting Earth's atmosphere toward its current oxidizing state.

Table 166: Dimensional Positions for known Ecosystem Engineers [adapted from (Jones, et al. 1994, Laland, et al. 1999, Hastings, et al. 2007)]

Organism	Properties						
	Organism Type	*Control*	*Influence*	*Resource Flow Modulation*	*Intention*	*Duration*	*Spatial Extent*
Beaver, Castor Canadensis	Allogenic	Bottom-up; asymmetric in the sense that they influence the fate of other organisms without being influenced	Modification to physical structure of land, nutrient flows and storage, fauna and flora communities	Nutrient, carbon and water resources affected	Phenotype	Medium; decades	Meters to a few kilometers
American alligator, Alligator mississippiensis	Allogenic	?	Modification to land structure	Retains water during droughts, causing limited hydrological impacts	Accidental	Short	?
Rabbits, Oryctolagus cuniculus; Badgers, Meles meles	Allogenic	?	Modify sub-surface and surface land forms	Provides habitat	?	Medium	Meters to ?
Marine phytoplankton	Autogenic	Bottom-up in the sense that many plankton interact	Absorb and scatter sunlight; establish thermoclines	Modulate radiant input to seas	?	?	10s of km?

Organism	Properties						
	Organism Type	*Control*	*Influence*	*Resource Flow Modulation*	*Intention*	*Duration*	*Spatial Extent*
		with sunlight to establish thermolcines					
Microalgae in sea ice	Autogenic	Bottom-up in the sense that many algae interact with sunlight to modify ice characteristics such as strength	Absorb and scatter light in ice and sea water; weaken ice and accelerate melting	Modulate radiant input to sea and sea ice	?	?	1000s of km?
Freshwater phytoplankton	Autogenic	?	Intercepts light; modifies thermal properties of water column	Modulate radiant input to freshwater	?	?	km?
Cyanobacteria and nonvascular plants	Allogenic	?	Modifies land surface in desert and semi-desert areas	Modulates water flux and storage; reduces soil erosion	Phenotype?	?	?
Bog moss, Sphagnum spp.	Autogenic	?	Changes land structure and hydrology	pH, water resources affected	?	Long	100s of km?
Submerged macrophytes	Autogenic	?	Attenuate light, retard flow and add oxygen	Radiant, water and oxygen resources affected	?	?	?
Forest trees (broad-leaved	Autogenic	?	Change land structure; influence	Nutrient, carbon and water	Accidental	Medium to long	Meters to km (for streams)

Organism	Properties						
	Organism Type	*Control*	*Influence*	*Resource Flow Modulation*	*Intention*	*Duration*	*Spatial Extent*
and conifers)			hydrology	resources affected			
Higher plants	Autogenic	?	Modification to soil surface properties caused by leaf litter	Radiant flux, hydrology and gas exchange influenced	?	Medium to long	cm to km
Terrestrial plants	Autogenic	?	Water impounded in leaves by plants	Water resources slightly affected	Accidental?	Short; days	cm
Marine meiofauna (protozoa, etc.)	Allogenic	?	Changes in sea surface and water column caused by deposition, mechanical action and waste production	Physical changes to sea floor sediment; nutrient flows affected	?	?	<mm
Marine burrowing macrofauna	Allogenic	?	Sea floor structure changes	Nutrient and oxygen exchange with sediments heightened	?	?	?
Marine zooplankton	Autogenic	?	Filters water; concentrates nutrients and other compounds into fecal pellets	Important means of transporting nutrients in oceans	Accidental?	Seconds for pellet creation; long for nutrient cycling	Microscopic?
Fiddler crab, Uca pugnax	Allogenic	?	Changes tidal zone land structures by	Effects hydrology and oxygen	?	?	Meters

Organism	Properties						
	Organism Type	*Control*	*Influence*	*Resource Flow Modulation*	*Intention*	*Duration*	*Spatial Extent*
			burrowing	supply in coastal areas			
European periwinkle, Littorina littorea	Allogenic	?	Influences sedimentation on beaches	Sediment deposition reduced	?	?	?
Snails, Euchondrus spp.	Autogenic	?	Modifies rock surfaces	Increasing nitrogen cycling and soil formation	?	?	Meters?
Bagworm caterpillars, Penestoglossa sp.	Allogenic	?	Modifies rock surfaces	Increased nutrient cycling, erosion rate and soil formation	?	?	Cm?
Mound-building termites, Isoptera	Allogenic	?	Modifies land surface and subsurface	Influences hydrology and soil composition	?	Medium to long; decades to 1000s of years	Meters to 100s of meters
Ants, Formicidae	Allogenic	?	Change land or subsurface structure	Influences soil composition	?	Short; years?	Meters
Orb Weaver Spiders	Allogenic	?	?	?	Phenotype?	Short; days?	cm
Earthworms, Lumbricidae Megascolecidae	Allogenic	?	Change subsurface land forms	Influence nutrient cycles, hydrology and subsurface	?	Short; <1 year	cm

Organism	Properties						
	Organism Type	*Control*	*Influence*	*Resource Flow Modulation*	*Intention*	*Duration*	*Spatial Extent*
				land forms			
Blind mole rats, Spalax ehrenbergi	Allogenic	?	Change subsurface land forms	Increases subsurface air supply / oxygenation	?	?	?
Mole rats, Bathyergidae	Allogenic	?	Change surface land forms	Affects soil formation	?	?	Km?
Prairie Dogs, Cynomys spp.	Allogenic	?	Changes surface and subsurface land structure	Influences soil chemistry and other properties	?	Long; centuries to millenia	Km?
Pocket gophers, Geomys bursarius	Allogenic	?	Change surface and subsurface land forms	Affects nutrient availability, soil development	?	Short; a few years	10s of meters
Indian crested porcupine	Allogenic	Accidental	Change surface land forms	Increases concentration of water and nutrients	?	Medium; 20 years	cm
Elephants, Loxodonta africana	Allogenic	?	Disturbance and destruction of flora	Affects soil formation and biogeochemical cycling	?	?	km?
Crustose coralline algae, Porolithon Lithophyllum	Allogenic	?	Alter sea floor	Change coastal hydrodynamics, nutrient cycling	?	Long; potentially 100s of millions	100s – 1000 km

Organism	Properties						
	Organism Type	*Control*	*Influence*	*Resource Flow Modulation*	*Intention*	*Duration*	*Spatial Extent*
						of years	
Ribbed mussels, Geukensia demissa	Allogenic	?	Change marsh floor structure	Fix sediments	?	?	Meters?
Lepidopteran, pseudotelphusa spp.	Allogenic	?	Change forest canopy	?	?	Short; months	10s of cm
Eriophyis mite, Calacarus flagelliseta	Allogenic	?	Change forest canopy	?	?	Short; months	cm
Humpback whale, Meguptera novaeangliae	Allogenic	?	Bubble nets	?	?	Very short: minutes	10s of meters
Soft shell clam, Mya arenaria	Autogenic	?	Alters sea floor structure	?	?	Long; century	km
Cordgrass, Spartina anglica	Autogenic	?	?	?	?	Short; years	Meters to 10s of meters
Sunfish, Centrarchidae	Allogenic	?	Nests?	?	?	Short; year	cm to meters
Stingray, Dasyatid ray	Allogenic	?	Alters sea floor structure	?	?	Very short; days	10s of cm

Coder	John Reap	Date	1/22/2008
Type	Theoretical Memo		
Category	Feedback		
Title	?		

The Feedback Category contains concepts for the signal and the entities generating the signal (See Figure 65). The two general classes of feedback, positive and negative, appear, and the idea of scale enters the picture in the form of the top-down control property. Some overlap may be present in the form of the influence property and the signal property for the two listed concepts. That is, signal strength and influence may refer to similar ideas.

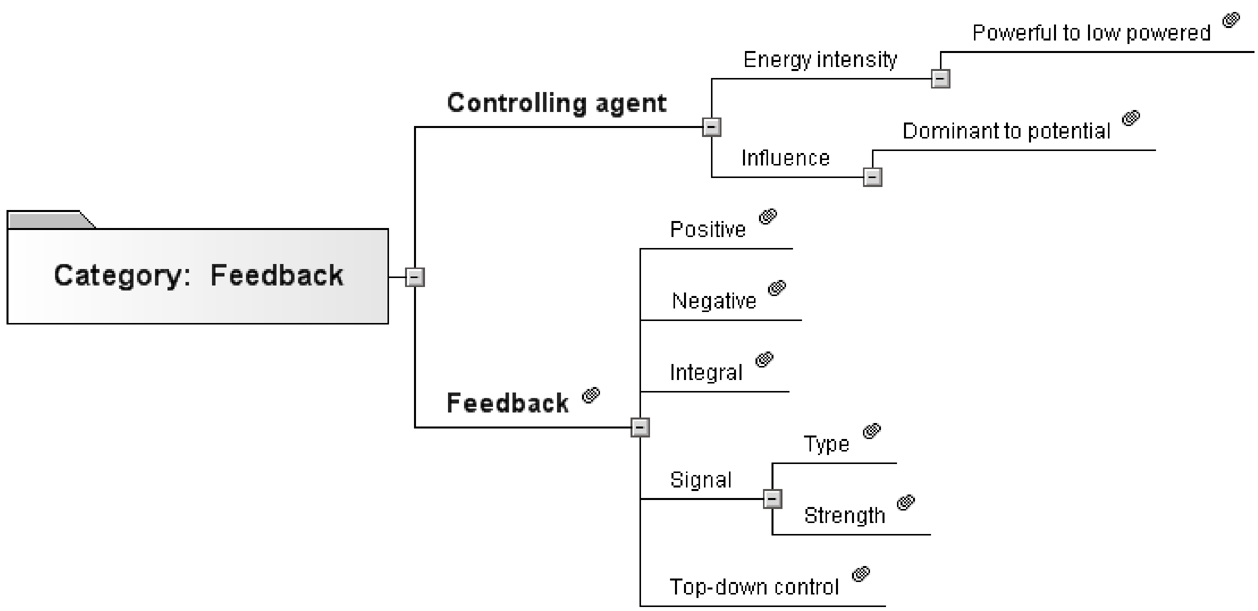


Figure 69: Feedback Category with Properties and Dimensions

The top-down control property reminds me of the work of Allen and Starr and some of the ideas discussed in Bryon Norton's Adaptive Management Class. In those contexts, collections of small scale actors exerted influence on the entire assemblage while larger scale actors simultaneously constrained and controlled the small actors. Powers' memo connects top-down control with feedback in the form of keystone species. Keystone species exert top-down control on the communities in which they inhabit, which connects this category to those dealing with organism interactions and interaction webs.

I suspect connections with other categories could also be made, and this suspicion makes the derivation of insights from the feedback category difficult. On multiple occasions, I came to the conclusion that feedback enables other interesting biological phenomena after reviewing code notes. It did not seem to stand on its own as a distinct category.

Coder	John Reap	Update	1/30/2008

The properties of influence and signal are not the same as suggested in the first paragraph of this memo. Signal refers to the classical notion in control theory, inputs and outputs from a block diagram that represents a kind of transfer function. Influence, on the other hand, refers to the importance of a controlling agent in a system. Both important and unimportant controlling agents can have strong signals, but the system will more readily respond to an agent with dominant influence. Vermeij's influence also implies that systems that change states can also change controlling agents, hence the dimensional position labeled "potential."

Coder	John Reap	Date	1/21/2008
Type	Theoretical Memo		
Category	Interaction Webs		
Title	Form and Function in Interaction Webs		

Reviewing the concepts and their respective properties for the Interaction Web Category diagramed in Figure 65, one notices two general classes of properties. One class attempts to describe the abstract form of interaction webs. Properties of this class describe the structure, size, complexity and composition of these webs. The other class attempts to describe their general behavior or response to stimuli. Such properties include: stability, resilience, vulnerability, persistence and productivity. The former class is more readily quantified. One can count nodes, catalog types of components, measure interaction strengths and frequencies and derive metrics for complexity. Of course, one can also quantify behaviors such as productivity, and in biology, some metrics for this particular behavior (i.e. NPP) exist. Indicators for behaviors such as stability and resilience are harder to define. When it comes to understanding an ecologist's motivation for studying these properties, the situation reverses. It is clear that properties in the second class would be of interest, but why does someone wish to count nodes or measure interaction frequencies?

It seems reasonable that one answer to this question is that the properties in the first class are related to those in the second. Webs with certain abstract forms display certain behaviors, and ecologists want to associate the more measurable properties of the first class with the more interesting ones in the second. Causal links between quantifiable quantities in the first class and interesting qualities in the second would form foundations for the principles which I seek. A memo exploring these relationships and associating biological metrics would be a useful exercise.

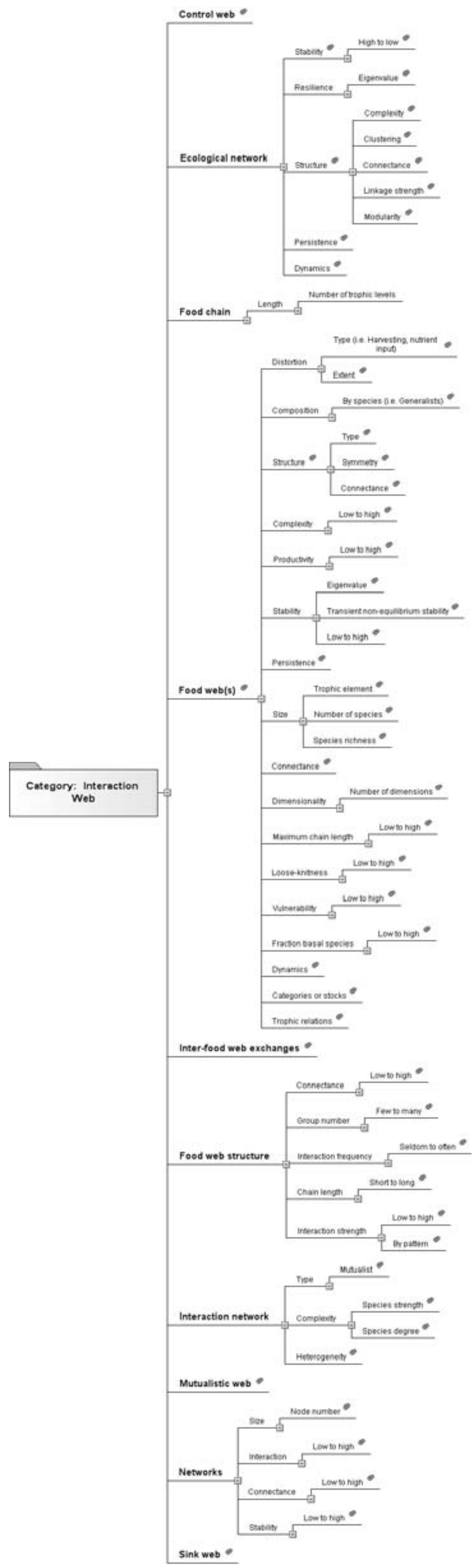


Figure 70: Interaction Web Category with Properties and Dimensions

Coder	John Reap	Date	1/30/2008
Type	Theoretical Memo		
Category	Interaction Webs		
Reference	Interaction_web_theoretical_1.memo		
Title	Metrics and Measures for the Properties and Dimensions of Interaction Webs		

At the close of the first theoretical memo about Interaction Webs, I noted that a discussion of metrics and measures connected with its properties might advance my understanding of the category (See Interaction_web_theoretical_1.memo). This theoretical memo attempts such a connection. It lists and explains the various metrics and measures associated with the properties. It notes their uses in biology and comments upon their potential applications in industrial systems.

Multiple dimensions for ecological networks receive treatment in Montoya's paper (Montoya, et al. 2006). He mentions complexity, connectance, linkage strength, clustering, modularity and eigenvalue. Reasonably clear and mathematically operational definitions for complexity (C_p) and connectance (C) appear in his paper. Both are functions of the total number of links (L) and species (S) in a web.

$$C_p = \frac{L}{S} = \frac{\sum_{i=1}^{n} L_i}{S}$$

$$C = \frac{L}{S(S-1)} = \frac{\sum_{i=1}^{n} L_i}{S(S-1)}$$

Two caveats apply to the calculation of connectance. Since it is a ratio of existing web links to mathematically possible web links, the denominator is S^2 if cannibalism occurs. Some calculate connectance using 2L as the numerator; Warren provides an explanation for this latter approach (Warren 1990). Returning to complexity, other metrics emerge when one considers the more general concept of interaction networks. Species strength and species degree are two such metrics (Bascompte, et al. 2006). Species strength is calculated by summing the dependences of other species on the organism in question. Species degree refers to the number of interactions per species in a network.

Linkage strength measures the effect of one species on the growth rate of another (Montoya, et al. 2006). Reiterating the work of Berlow and coworkers, one can state this mathematically by starting with the population density (N_i) for a species that exhibits a per capita growth rate (f(N_1,...N_n)) dependent on one or more other species in the web (Berlow, et al. 2004). One starts with the change in density of species *i*.

$$\frac{dN_i}{dt} = N_i f(N_1,...N_n)$$

One finds the interaction strength (a_{ij}) between the two species by taking the partial derivative of species *i*'s per capita growth rate with respect to the population density of species *j* (N_j).

$$a_{ij} = \frac{\partial}{\partial N_j}\left(\frac{1}{N_i}\frac{dN_i}{dt}\right) = \frac{\partial}{\partial N_j}\left(f(N_1,...N_n)\right)$$

It should be noted that the traditional approach to determining interaction strengths is based on Lotka-Volterra equations (de Ruiter, et al. 1995).

Clustering describes a pattern of interactions in which one organism interacts with a set of organisms that also tend to interact with each other. Clustering coefficients (C_i) for individual nodes and whole systems (i.e. average cluster coefficients ($\overline{C_i}$)) quantify this pattern. The clustering coefficient is a ratio of links between nodes in the neighborhood of node *i* and the total number of possible links between these nodes. Defining the neighboring nodes as k_i and the existing links between these nodes as l_i, one can write an equation for the clustering coefficient.

$$C_i = \frac{2l_i}{k_i(k_i - 1)}$$

Interestingly, this equation is similar to the one for connectance and is identical to the alternate form of the connectance equation. Clustering and connectance are the same? The average clustering coefficient is simply the sum of all clustering coefficients divided by the total number of nodes (n) in the network.

$$\overline{C_i} = \frac{\sum_{i=1}^{n} C_i}{n} = \left(\frac{2}{n}\right)\sum_{i=1}^{n} \frac{l_i}{k_i(k_i - 1)}$$

Both of the previous two formulas apply to undirected graphs. Undirected graphs allow only one link between two nodes, not a link for each direction. Directed graphs differentiate between a link going from node *i* to node *j* and one going from node *j* to node *i*. As a result, directed graphs possess twice as many links as undirected graphs.

Pimm and Lawton use a "compartmentalization statistic" to gage modularity in food webs (Pimm, et al. 1980). Unfortunately, their heuristic is limited to situations where webs possess the same connectance, number of species and "other properties."

Eigenvalue, the last metric mentioned by Montoya, appears in a few sentences near the end of his paper. These eigenvalues seem to apply to matrices for linearized food and mutualist webs. Apparently, the magnitude and sign of eigenvalues determines the resilience of a system; large, negative values indicate a system that quickly returns to its previous state following perturbation. Interestingly, more complex systems possess larger negative eigenvalues (Montoya, et al. 2006). But, the frequency of initially stable systems declines as complexity increases (Montoya, et al. 2006). I imagine that finding an eigenvalue for a food web is similar to the approach taken for any other system of equations represented by a matrix. One must first have a matrix, though.

Moving to the concepts of food chains and webs, one finds multiple size measures. Length of a food chain is measured in trophic elements. A chain with length three possesses a producer and two levels of consumers, for example. One measures food web size by: number of species, maximum chain length, composition and species richness. The last three of these require some explanation. Maximum chain length is simply the longest feeding path found in the web. Composition refers to the feeding habits of the species represented by nodes in the web. One might have producers, herbivores, carnivores, omnivores, etc. Species richness has the same meaning as number of species (Briand 1983).

Rooney introduces a unique dimension for a food web's structure property. Symmetry describes the degree to which energy flow in a food web's channels varies from balanced to asymmetric (Rooney, et al. 2006). If biomass production is balanced by biomass loss and consumption (equilibrium), Rooney calculates energy flow for an individual consumer by dividing the sum of biomass production by total biomass.

$$v_c = \frac{e\sum_{i \in R} CF_{CR_i}}{C}$$

His relation equates biomass turnover (v_c) with energy flow. Its calculation requires knowledge of conversion efficiency (e), consumer biomass (C) and the effect of each resource R_i on the consumer. This effect (F_{CR_i}) is not well defined; he opaquely refers to it as a "functional response" (Rooney, et al. 2006).

He observes that asymmetric energy flow is a characteristic of more stable food webs. Stability is again defined as "the most negative eigenvalue" (Rooney, et al. 2006). However, he also introduces a metric for dynamic stability that incorporates the rate of return to equilibrium ($\frac{D_R}{T_R}$) and overshoot (D_{os}). His transient non-equilibrium stability metric (S_{tne}) divides the average rate of return to equilibrium by the height of the system's overshoot.

$$S_{tne} = \frac{D_R}{T_R D_{os}}$$

It seems likely that this type of response analysis might benefit from the introduction of ideas from classical controls theory.

Schoener introduces multiple unique metrics for food webs (Schoener 1989). Of these, fraction basal species, loose-knitness and vulnerability seemed most intriguing when coding his paper. The fraction of basal species is simply the ratio of species without prey to the total number of species in a web. One calculates loose-knitness by finding the mean of the minimum food chain distances. The presence of multiple minimum chains implies the existence of a categorization value for chain length. One needs a quantitative criterion when selecting chains small enough to become part of the minimum category, but such a criterion is not explicitly stated in Schoener's paper. Vulnerability is defined as the mean number of predators per prey species. Operationally, one takes the average of the ratios of predators to prey.

Coder	John Reap	Date	4/8-11/2008
Type	Theoretical Memo		
Category	Interaction Webs		
Reference	Interaction_web_theoretical_3.memo		
Title	Interaction Web Literature: A "Brain Dump"		

This memo summarizes ecological interaction web literature collected during the course of two literature surveys. The first survey occurred as part of a larger effort to identify biologically inspired sustainability principles by application of constant comparative method to biology literature. A review centered on particular types of interaction networks constitutes the second literature survey. It is being prepared as a roughly crafted briefing document meant to support the composition of an NSF grant on biological networks and engineering infrastructure.

Traditional Food Web Structural Analysis

Robert M. May

In the early 1970s, May proposed a set of stability criteria derived using mathematical reasoning and simulation (May 1972). He constructed a set of equations linking species populations x to changes in the size of each population using an interaction matrix A.

$$\frac{d\vec{x}}{dt} = \mathbf{A}\vec{x}$$

He constructed the interaction matrix from the identity matrix I and an n x n matrix B populated by randomly generated elements possessing a mean value of 0 and a mean square value α. May considers the mean square value, α, an average interaction strength.

A = B – I

The system of differential equations was considered stable if all eigenvalues of A had negative real components. For large number of species (S), he found the following stability criteria expressed in terms of interaction strength, species number and connectance. Connectance (C) is the ratio of links in a web to the topologically possible number of links.

$$\text{Stability likely if: } \alpha < (SC)^{-0.5}$$

$$\text{Instability likely if: } \alpha > (SC)^{-0.5}$$

These findings allowed him to argue that webs with strong interactions or high connectance would tend toward instability. He also believed two webs were similar in stability if the product of connectance and squared interaction strength proved approximately equal.

$$\alpha_1^2 C_1 \approx \alpha_2^2 C_2$$

Peter C. de Ruiter

Having constructed material flow diagrams and associated Jacobian community matrices for seven soil food webs, de Ruiter and coworkers varied interaction strengths to estimate their impact on system stability (de Ruiter, et al. 1995). They observed that interaction pattern strongly influenced system stability. They described these patterns as displaying top down affects at higher trophic levels and bottom up affects at lower trophic levels. The precise meaning of top-down and bottom-up is not clear in their article. Paradoxically, changes in "energetically unimportant" links sometimes reduced stability while changes in high energy links failed to affect it.

P.H. Warren

Warren examines the relationships among species number (S), link number (L) and connectance (C) in food webs (Warren 1990).

$$C = \frac{L}{S(S-1)}$$

Specifically, he investigates three hypotheses concerning the previously observed inverse relationship between species number and connectance. The first hypothesis states that C falls with S to preserve system stability. Here, stability is the same as that defined by May (May 1972). The second states that basic biological constraints related to anatomy, behavior and the like produce the relationship. The final hypothesis argues that the observed decline in connectance with increasing species number is an artifact of incomplete sampling. As species number rises, the effort required to identify all trophic links increases. Supporters of the third hypothesis argue that such a situation may lead to lower linkage counts in larger webs.

Combining new samples and published data, Warren constructs plots of L vs. S and C vs. S for natural food webs and discusses his findings (Warren 1990). He concludes that the second and third hypotheses are more likely correct. He also observes that most values for L fall between the limits L=S-1 and $L=k(S^2-S)/2$ when plotted against S, where k is a constant.

Neo-Structural Food Web Analysis

Jordi Bascompte

Bascompte and coauthors examined mutualistic interactions between plants and pollinators or seed dispersers (Bascompte, et al. 2006). They found that mutualistic network architectures were characterized by dependency asymmetries, few strong dependences and heterogeneity in species strength. Dependency was measured in terms of numbers of visits by a species of pollinator or seed disperser to a plant species. A plant with a large fraction of its total visits coming from a single pollinator or disperser would be considered strongly dependent on that visitor. Similarly, a pollinator or disperser with a large fraction of its total visits dedicated to a particular plant species would be considered strongly dependent on that plant species. Asymmetry in dependence means that plants and their visitors tended not to share mutually strong dependences. In other words, if one depended strongly on the other, the other did not depend strongly on the one.

Interestingly, they believe that asymmetric dependences enhanced community coexistence. Using mutualistic models partially based on May's work, they identified an inequality that defined a threshold for, "…positive community steady state (community coexistence)…" (Bascompte, et al. 2006).

$$\alpha\beta < \frac{ST}{nm}$$

The product of the average per capita effects of animals on plants (α) and plants on animals (β) must not exceed the product of average interspecific competition coefficients (S and T) divided by the number of species of plants (n) and animals (m) to achieve steady state. One must note that this finding is based on the simplest scenario.

Jonathan M. Chase

Chase discusses the perceived similarities and differences between terrestrial and aquatic food webs as well as hypotheses meant to explain them (Chase 2000). He concludes that available evidence is insufficient to support or refute the presented hypotheses.

Jose Montoya

Montoya and coauthors review ecology and network literature with the intent to, "…compare ecological networks to non-ecological networks, and consider their similarities, differences and underlying causes" (Montoya, et al. 2006). However, they dedicate most of the article to discussing ecological networks and models of ecological networks. Though they eventually conclude that ecological network knowledge is incomplete, they identify some intriguing trends.

These trends include:

Species are close if one counts distance in terms of links. Only 2-3 links separate the species in the webs that they examined.

No general consensus exists about compartments and clustering in ecological networks, but two exceptions exist. First, food webs form compartments at habitat boundaries, and two, tight clusters form in host-parasite systems.

Interestingly, more complex model systems possess larger negative eigenvalues - are more stable. But, the frequency of initially stable systems declines as complexity increases.

Along the way, they define a number of terms and metrics commonly encountered when reviewing literature about networks and ecological networks. They mention complexity (

C_p), connectance, linkage strength, clustering, modularity and eigenvalue. Complexity is merely the number of links (L) divided by the number of species (S) in a web.

$$C_p = \frac{L}{S}$$

Linkage strength measures the effect of one species on the growth rate of another; it seems synonymous with interaction strength. Clustering describes a pattern of interactions in which one organism interacts with a set of organisms that also tend to interact with each other. Clustering coefficients (C_i) for individual nodes and whole systems (i.e. average cluster coefficients ($\overline{C_i}$)) quantify this pattern. The clustering coefficient is a ratio of links between nodes in the neighborhood of node *i* and the total number of possible links between these nodes. Defining the neighboring nodes as k_i and the existing links between these nodes as l_i, one can write an equation for the clustering coefficient.

$$C_i = \frac{2l_i}{k_i(k_i - 1)}$$

Interestingly, this equation is similar to the one for connectance and is identical to the alternate form of the connectance equation. Clustering and connectance are the same? The average clustering coefficient is simply the sum of all clustering coefficients divided by the total number of nodes (n) in the network.

$$\overline{C_i} = \frac{\sum_{i=1}^{n} C_i}{n} = \left(\frac{2}{n}\right)\sum_{i=1}^{n} \frac{l_i}{k_i(k_i - 1)}$$

Both of the previous two formulas apply to undirected graphs. Undirected graphs allow only one link between two nodes, not a link for each direction. Directed graphs differentiate between a link going from node *i* to node *j* and one going from node *j* to node *i*. As a result, directed graphs possess twice as many links as undirected graphs. Modularity is mentioned though not discussed in any detail. Eigenvalue, the last metric mentioned by Montoya, appears in a few sentences near the end of his paper. These eigenvalues seem to apply to matrices for linearized food and mutualist webs. Apparently, the magnitude and sign of eigenvalues determines the resilience of a system; large, negative values indicate a system that quickly returns to its previous state following perturbation.

Neil Rooney

Rooney and coworkers analyzed energy flows in terrestrial and aquatic food webs using annual carbon production and production to biomass ratio as proxies for energy flow (Rooney, et al. 2006). They identified "fast" and "slow" energy channels coupled by "mobile higher-order" consumers. This asymmetry of coupled energy flows appeared in many ecosystems. According to the authors' analyses, these asymmetries conferred both equilibrium and non-equilibrium stability on ecosystems. Equilibrium stability seems to correspond to the idea of resistance while non-equilibrium stability seems synonymous with resilience.

Beyond the Web: Outside Influences

Frederic Briand

Analysis of 40 real food webs indicates that connectance declines as the variability of the physical environment increases (Briand 1983). Variable physical parameters include temperature, salinity, pH, water availability and others. Following a line of reasoning strongly influenced by May's theoretical analysis (May 1972), he argues that feeding behavior is the proximate cause of the difference between connectance values for webs in stable and unstable environments. Limitations in feeding periods caused by environmental fluctuations lead organisms to depend upon intermittent, intense feedings. Brian argues that this approach to feeding raises the average interaction strength (α), which requires a corresponding decrease in connectance (C) to maintain system stability. This argument is based on a version of May's stability criteria.

$$\alpha(SC)^{0.5} < 1$$

As previously stated, S is the number of species in the food web. He believes interaction strength can be lower and connectance higher in a more stable environment because organisms can depend upon a more reliable supply of food.

Alan Hasting

Hastings article primarily focuses on ecosystem engineers. However, he makes a point of mentioning how ecosystem engineering influences trophic interactions. He states that:

"…[ecosystem] engineering may affect the spatial heterogeneity that is important in the organization of food webs (e.g. resource distribution patterns)."

"…food webs narrate only part of the story of interactions among species and their environment…organisms engage in both trophic and engineering interactions to some degree."

K.N. Laland

Using an entirely theoretical model, Laland and coauthors demonstrate that niche construction (a.k.a. ecosystem engineering) can alter evolutionary processes and, therefore, influence ecological patterns. Niche construction is the modification of the physical environment by an organism. It includes activities as simple as shading and as complex as coral reef formation.

Boundaries

Tiffany M. Knight

Knight and coworkers studied simple pond and terrestrial food webs coupled by a predator (Knight, et al. 2005). The pond food web consisted of a predatory interaction between fish and dragonfly larvae. The terrestrial food web involved predation by adult dragonflies on pollinators and pollination of shrubs. Shrubs adjacent to ponds without fish were visited by fewer pollinators than those adjacent to ponds with fish. Fish predation reduced dragonfly larvae. Fewer larvae meant fewer dragonflies menacing pollinators which allowed more pollinators to visit shrubs. This finding illustrates that a trophic cascade (strong impact of a predator on some subset of organisms in a food web) can cross food web boundaries if one or more coupling organisms exists.

M.L. Cadenasso

This article discusses the structure, function and importance of food web boundaries (Cadenasso, et al. 2004)…

Sub-nodal Properties

Woodward and coauthors review literature on the relationship between ecological networks and body size. The following table cut from their paper summarizes their findings (Woodward, et al. 2005).

Table 1. Examples of relationships between body size and ecological traits, and the potential implications for the structure and/or dynamics of ecological networks[a]

Trait and relationship with body size [+/−]	Within nodes	Between nodes	Network	Refs
Number of size-classes (~cohorts) [+]	Potential for cannibalism and/or cohort dominance	Potential ontogenetic reversals of trophic status	Potential for intraguild predation, self-damping and feeding loops increases towards top of the web	[15,24]
Numerical abundance [−]	More small than large individuals	Prey are more abundant and are smaller than predators	Trophic pyramid of abundance	[2,9,10,15,23]
Trophic status [+]	Larger individuals are more carnivorous	Prey are smaller than predators	Assimilation efficiency increases towards top of the web	[10,15]
Diet width [+(−)]	Diet widths expand during ontogeny	High diet overlap among similar-sized species; size constraints on feeding links	Nested vertical hierarchy of feeding niches; size-delimited 'subwebs' within the community web	[15]
Secondary production [+]	Larger individuals are more productive	Production:biomass (PB) ratios are lower for predators than prey	PB ratios decline towards the top of the web	[10]
Nutrient cycling rate [−]	Larger individuals immobilize nutrients for longer	Larger species have slower return times for nutrients; consumer-driven resource dynamics	Stoichiometric imbalances between resources and consumers	[5,33]
Species richness [−]	n/a	Small species have more potential competitors and predators	Triangular food webs; greater redundancy at lower trophic levels	[22,70]

[a]Examples of some of the consequences of these relationships are given in order of increasing scale of organization, from intraspecific (within-node) effects, to effects on pairwise consumer–resource feeding links (between-nodes), to effects that are manifested at the scale of the entire food web (network).

Model Food Web Systems

Lutz Becks

Becks and coworkers create a simple, easily manipulated experimental model of a food web using bacteria (Becks, et al. 2005). By manipulating abiotic inputs, they induce steady state, cyclical and even chaotic behavior in the size of the bacteria populations in their microcosm. The authors claim that their model allows the investigation of many theoretical questions in ecology and that it permits investigation of changes between dynamic states, resilience, the influence of perturbations and, "…the interplay between complex dynamics and biodiversity" (Becks, et al. 2005).

Miscellaneous

Steven S. Cousins

After discussing the history of ecosystem definitions, the author calls for the redefinition of ecosystems based on individual organisms instead of trophic levels (Cousins 1996). Specifically, he argues that the top predator in a food web determines the direction of energy flow in a geographic area corresponding to its territory. He defines this area as an Ecosystem Trophic Module (ETM) or photon shed. In this allusion to watersheds, the top predator forms a gradient for solar radiation just as a landscape's topography forms a gradient for water. He advances the notion that ETMs and the food webs that describe them define a basic unit for ecology. Since his definition clearly links to food webs which in turn link to species, he states that his approach provides a stronger link between ecology and the theory of evolution than those based on trophic levels.

Richard S. Ostfeld

Ostfeld and Keesing consider the influence of regular and sporadic increases in resource availability on ecosystem dynamics (Ostfeld, et al. 2000). They focus on "Mast seeding" events – large seed crops produced periodically by plants. The resource pulse tends to set a type of natural bull whip affect in motion. Herbivore populations reach a maximum while the pulse is already in decline, and carnivore populations similarly increase to a peak when herbivores are in decline. They also observe that generalist consumers seem best positioned to take advantage of periodic resource surges.

Coder	John Reap	Date	1/21/2008
Type	Theoretical Memo		
Category	Metabolic Limits		
Title	Metabolic Limits for Organisms and Networks		

Most concepts diagramed in Figure 65 deal directly with metabolism. Many deal with metabolism as conventionally defined in biology, but a few (energetic network constraint, metabolic requirements) point toward an extended notion of metabolism. A quick review of Moses' memo shows that the extended metabolism notion springs from Brown's work with energetic networks and appears a direct analog of the power law models used for individual organisms. The idea of universal metabolism limits is present both directly and indirectly in the gathered comments.

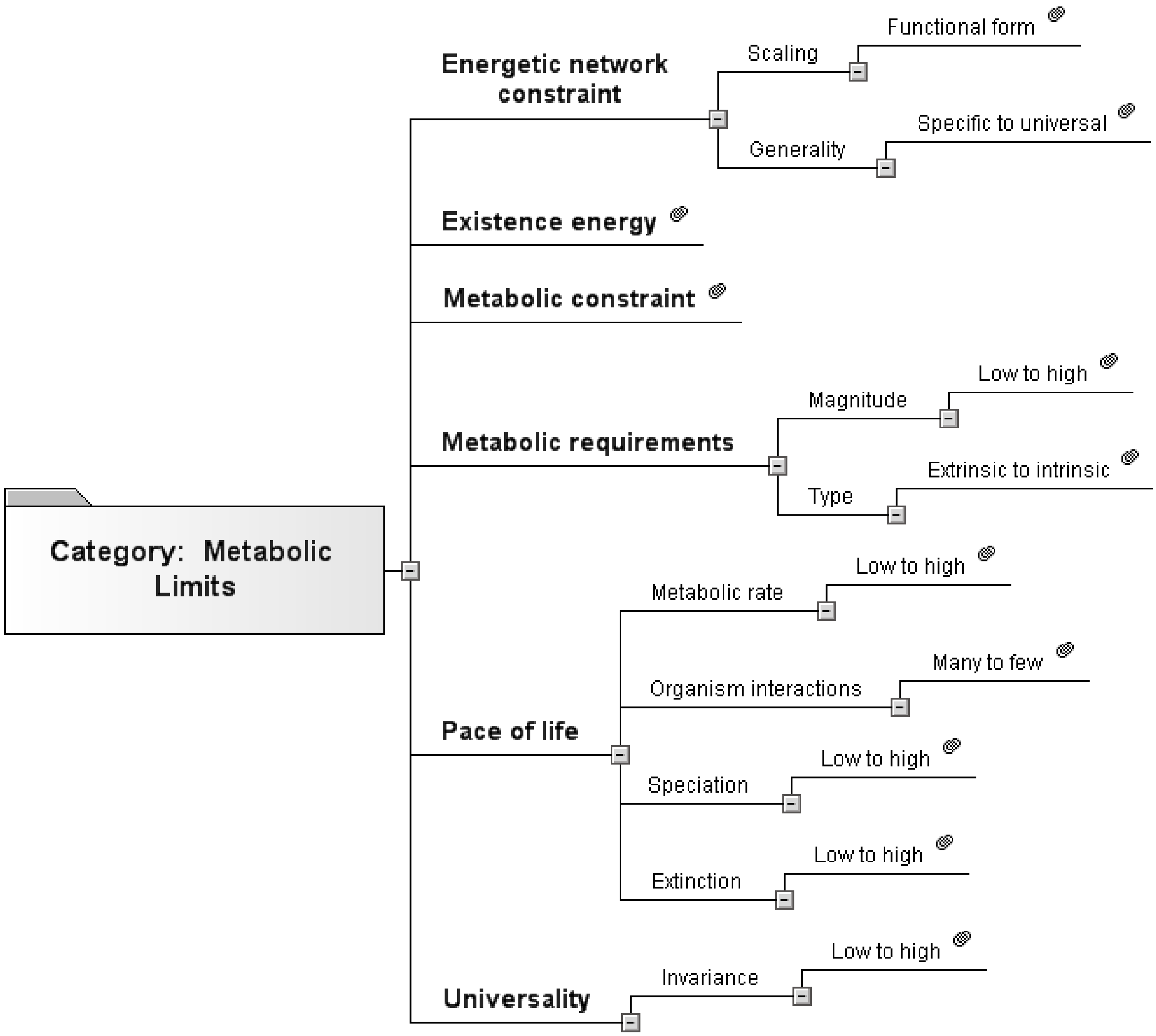


Figure 71: Metabolic Limits Category with Properties and Dimensions

Interestingly, the pace of life concept seems to connect metabolism with other organism characteristics. Its properties include those for daily activities and metabolic rates as well as evolutionary activities.

Coder	John Reap	**Update**	1/30/2008

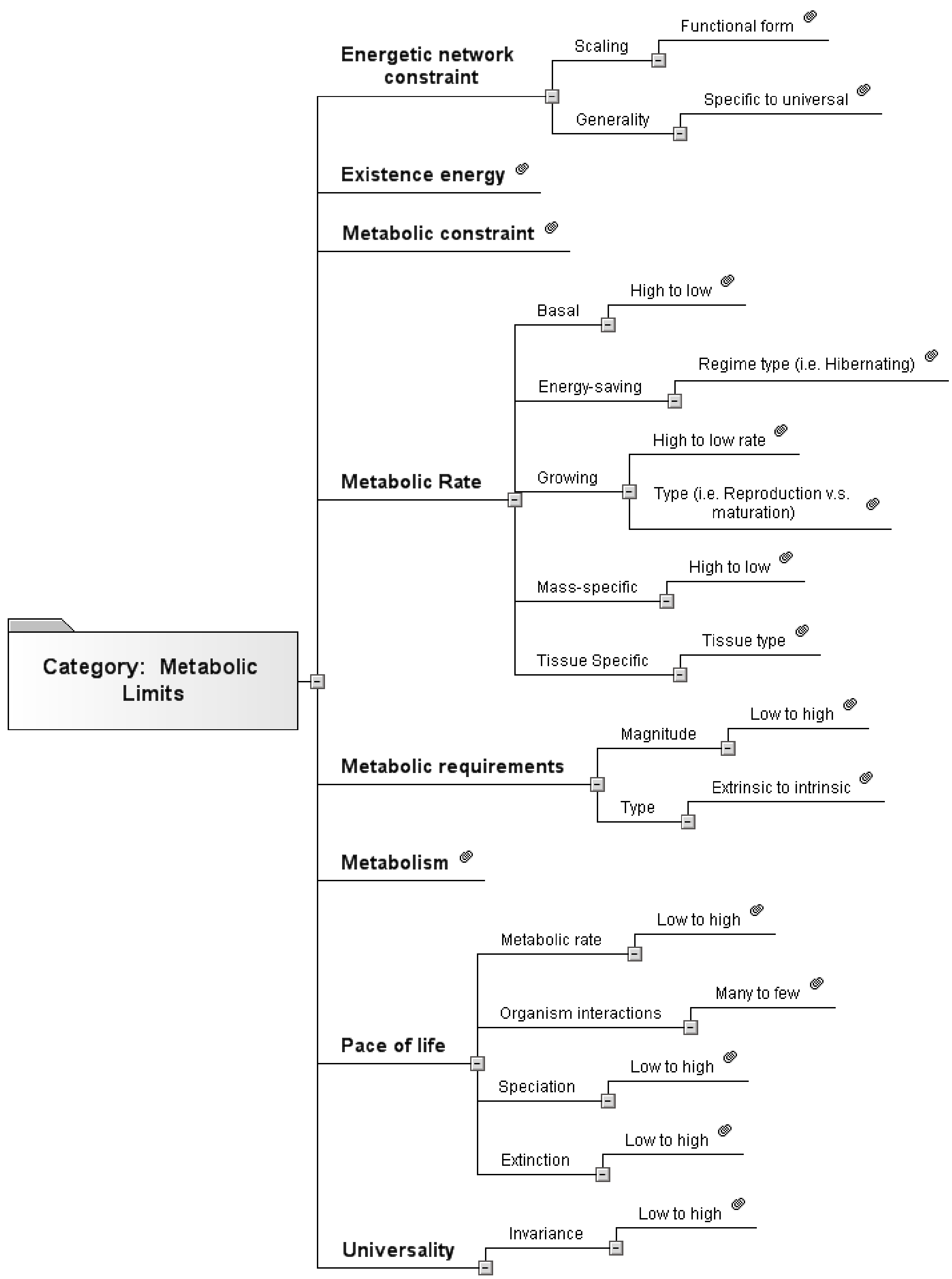


Figure 72: Metabolic Limits Category Updated with Makarieva's Concepts

Figure 72 contains concepts from a memo on Makarieva's work initially omitted during the construction of Figure 65. The new concepts and properties primarily reinforce ideas already present in the incorporated literature, but they add information about metabolic rate's dependence on life phase and living tissue. His paper contains enough information to quantify at least one of the dimensions listed under metabolic rate. These quantities could provide a range for the high to low dimension associated with the mass-specific property of the metabolic rate concept.

Coder	John Reap	Date	1/18/2008
Type	Theoretical Memo		
Category	Micro / nano structure influenced adhesion		
Title	Organizing concepts and finding gaps		

A number of the concepts diagramed in Figure 65 possess overlapping properties, and a few seem redundant. Microstructure and epidermal microstructure represent the same concept in the coded articles. They both refer to micro and, sometimes, nano-scale surface features that influence the behavior of solids and liquids on these surfaces. This observation is reinforced by the fact that both concepts have a number of properties in common: roughness, waxiness and hydrophobicity / water repellency. Biofouling and microfouling both refer to a similar idea; in fact, both fall under the more general heading of fouling. When thus condensed, a new property appears – type. The type of fouling would seem to vary from animate to inanimate. These changes condense the Micro / Nano Structure Influenced Adhesion category (See Table 167).

Table 167: Reorganized Concept, Property, Dimension Table for the Micro / Nano Structure Influenced Adhesion Category

Concept	Property	Dimension
Microstructure	Water repellency	Low to high
		Contact Angle
		Short to long duration
	Waxiness	Thick to thin
	Roughness	Low to high
		Type of geometry (convex, papillose, hairy)
		Slight to distinctive cell convexity
	Hierarchy	
	Anti-adhesion	Low to high
		Contaminant type
Fouling	Type	Animate or inanimate
	Initiating condition	Type (i.e. carbon residue deposition)
	Size	Micrometers
	Occurrence	Many to few
Self-Cleaning	Assistance	None to specific cleaning action
		Type (i.e. water, secretions, grooming, etc.)
	Passive	Type (i.e. nanorough surfaces)
	Active	Type (i.e. epidermal desquamation, air-water transition induced boundary layer reduction)
Adhesion		
Adhesion vs. self-cleaning tradeoff		

The concepts also divide into cause and effect. Concepts such as epidermal microstructure and microstructure are partially responsible for concepts focusing on effects: adhesion, self-cleaning, biofouling and microfouling. Some effects appear to be extreme examples of others. Self-cleaning, for instance, is simply an example of low adhesion. Adhesion vs. Self-cleaning Tradeoff points to a relationship.

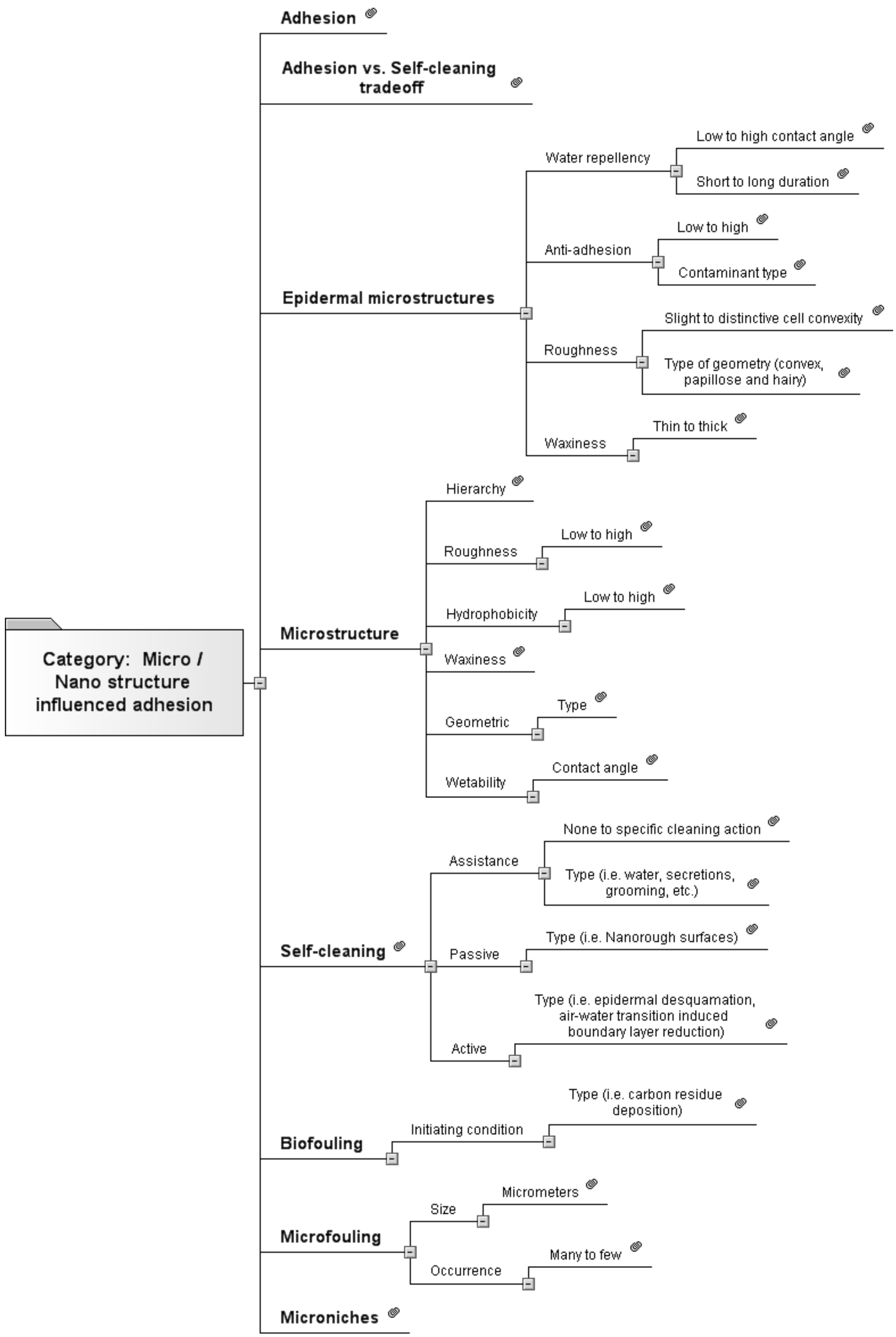

Category: Micro / Nano structure influenced adhesion
Adhesion
Adhesion vs. Self-cleaning tradeoff
Epidermal microstructures
Water repellency
Low to high contact angle
Short to long duration
Anti-adhesion
Low to high
Contaminant type
Roughness
Slight to distinctive cell convexity
Type of geometry (convex, papillose and hairy)
Waxiness
Thin to thick
Microstructure
Hierarchy
Roughness
Low to high
Hydrophobicity
Low to high
Waxiness
Geometric
Type
Wetability
Contact angle
Self-cleaning
Assistance
None to specific cleaning action
Type (i.e. water, secretions, grooming, etc.)
Passive
Type (i.e. Nanorough surfaces)
Active
Type (i.e. epidermal desquamation, air-water transition induced boundary layer reduction)
Biofouling
Initiating condition
Type (i.e. carbon residue deposition)
Microfouling
Size
Micrometers
Occurrence
Many to few
Microniches

Figure 73: Micro / Nano Structure Influenced Adhesion Category with Properties and Dimensions

Given my knowledge of some, as of yet, uncoded papers concerning surface adhesion, it seems likely that some models describing the range of adhesive behavior exist. Reviewing these models may provide insight into the relationship between identified causes and effects.

A series of papers by Autumn and coauthors explains many of the mechanisms responsible for Gecko adhesion and begin to illuminate the importance of surface roughness in the relationship between adhesion and self-cleaning (Autumn, et al. 2006, Tian, et al. 2006, Autumn 2007). It is the relationship among surface roughness, self-cleaning and adhesion that is of interest in this context. Equations for surface potential energy (E_x) and frictional force (F_f) parallel to two contacting planar surfaces are of particular interest (Tian, et al. 2006).

$$E_x = E_0 \sin\left(\frac{2\pi x}{x_0}\right)$$

$$F_f = \frac{-dE_x}{dx} = \frac{-2\pi E_0}{x_0}\cos\left(\frac{2\pi x}{x_0}\right)$$

E_0 is not discussed in Tian's work, but x_0 is described as a, "critical spacing related to atomic lattice, molecular or asperity dimension" (Tian, et al. 2006). Setting E_0 equal to 1 and plotting F_f for x[0,1] in increments of .01, one generates Figure 74. Each cosine wave represents the variation in frictional force along the direction parallel to two contacting planar surfaces for five different critical spacing values.

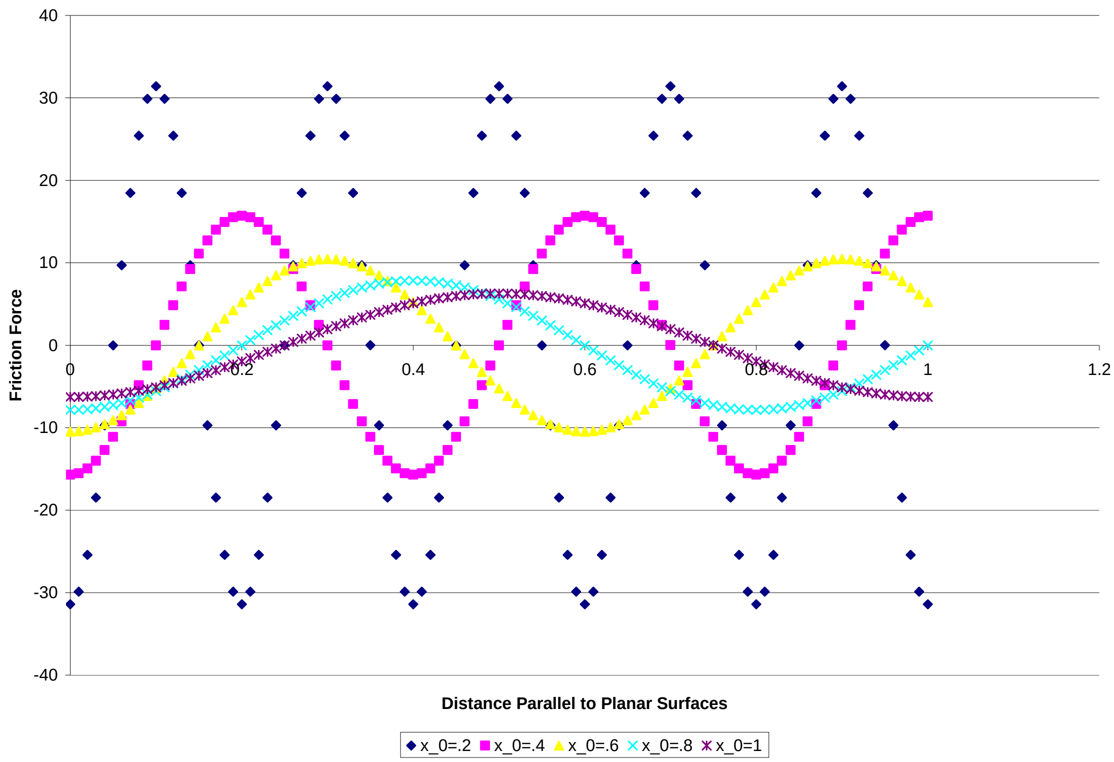


Figure 74: Friction Force for Two Contacting Planar Surfaces as a Function of Distance Measured Parallel to the Surfaces

This plot shows that frictional force amplitudes fall as critical spacing increases. In other words, one expects lower resistance to slipping as a surface becomes rougher, which might explain part of the resistance to soiling observed for micro and nanorough surfaces. This is a conclusion supported by Autumn and Hansen who state that natural self-cleaning behavior is, "…due to a micro- and nano-rough topology that reduces adhesion with solid and liquid surfaces" (Autumn, et al. 2006).

Logically, this model fails when the critical spacing approaches the size of one or more contacting surfaces. Surface features mechanically interlock, or one surface falls into the gap represented by the critical spacing distance in such situations. It may fail for other reasons; therefore, it would be wise to acquire and review some of the basic surface adhesion work referenced in Autumn's papers. Further consideration of the adhesion equations in Tian's work may also prove insightful.

Coder	John Reap	Date	1/22/2008
Type	Theoretical Memo		
Category	Mutualism and Cooperation		
Title	Behavior and Benefit		

Redundancy and a cleavage into two distinct groups of ideas are the two main features of the concepts in Figure 65. This memo discusses the latter and more important of the two. The concepts describe cooperative behaviors and resultant benefits; Table 168 classifies the diagramed concepts according to the behaviors and benefits grouping.

Behaviors	Benefits
Cooperation	Indirect Reciprocity
Cooperation in living systems	Network Reciprocity
Cooperative behavior	Reciprocation Theory
Mutualism	
Symbiogenesis	
Symbiosis	

Table 168: Concepts Grouped by Behavior or Benefit

Of these, concepts such as symbiosis are representative of the behavior group while indirect reciprocity is representative of the benefits group. The latter reveals the rationale for the former. Properties detailing behaviors provide insight into extent, stability, longevity and initiation criteria for cooperative relationships. Concepts which represent benefit arrangements lack properties, but the open coding memos from which they come contain cost-benefit relations from which one might tease them.

The questions of when and under what conditions cooperative relationships form and persist are important. Most creatures remain largely independent or even compete; so, clearly, these conditions are not always present. Other important questions center on the physical form of cooperative interactions and the more abstract form of the benefits exchange. How are benefits exchanged; do identifiable archetypes exist? What types of partnerships form? Partial answers to at least some of these questions, particularly the last one, can be found in Axelrod's paper. Attempts to answer these questions may lay the foundation for rules of cooperation in industrial systems. However, economic thinkers are likely ahead in this area, and therefore, it may not be the most productive use of my time.

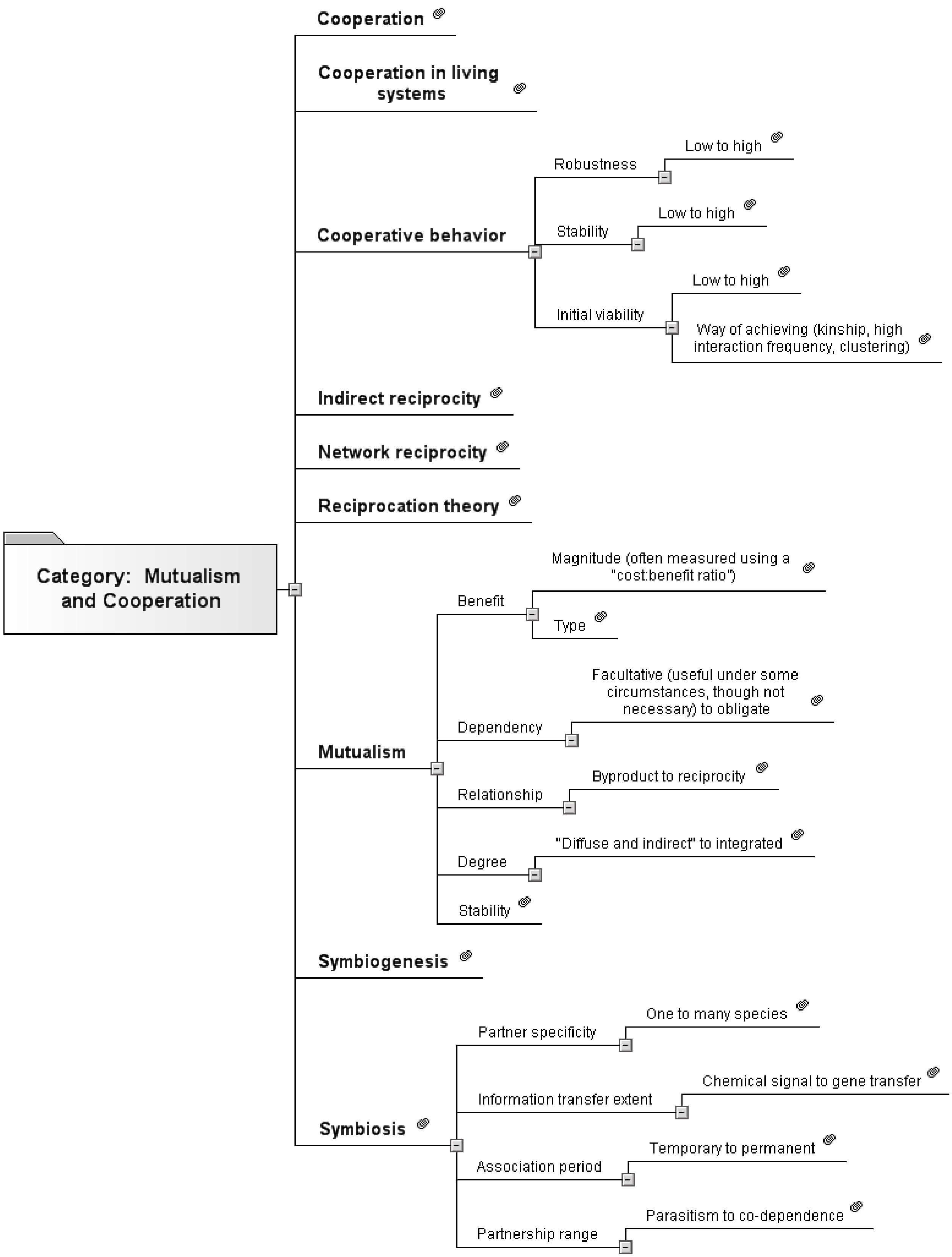

Category: Mutualism and Cooperation
Cooperation
Cooperation in living systems
Cooperative behavior
Robustness
Low to high
Stability
Low to high
Initial viability
Low to high
Way of achieving (kinship, high interaction frequency, clustering)
Indirect reciprocity
Network reciprocity
Reciprocation theory
Mutualism
Benefit
Magnitude (often measured using a "cost:benefit ratio")
Type
Dependency
Facultative (useful under some circumstances, though not necessary) to obligate
Relationship
Byproduct to reciprocity
Degree
"Diffuse and indirect" to integrated
Stability
Symbiogenesis
Symbiosis
Partner specificity
One to many species
Information transfer extent
Chemical signal to gene transfer
Association period
Temporary to permanent
Partnership range
Parasitism to co-dependence

Figure 75: Mutualism and Cooperation Category with Properties and Dimensions

Coder	John Reap	Date	1/24/2008
Type	Theoretical Memo		
Category	Organism Interactions		
Title	A Supporting Category		

Figure 65 contains multiple redundant properties. Strength is duplicated, and the types of organism interactions appear multiple times.

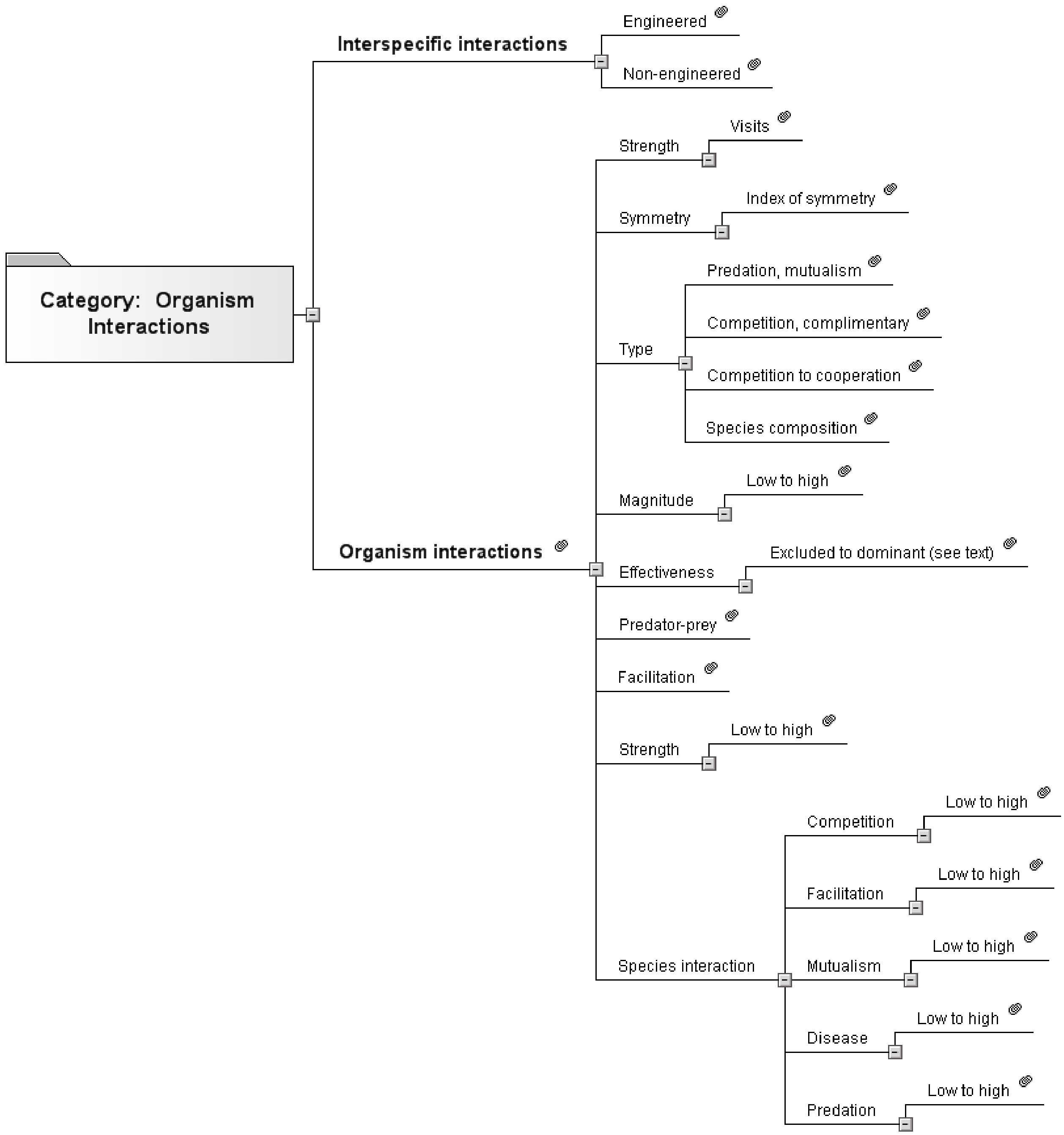


Figure 76: Organism Interactions Category with Properties and Dimensions

The type and species interaction properties refer to approximately the same idea, and elements of this idea appear as the predator-prey and facilitation properties. The existing tree can be condensed and clarified.

However, this category's connection to two other categories makes it of interest. The interactions present in this diagram connect the nodes of interaction webs and are the primary components of cooperative and mutualistic relationships. Learning about these relationships adds to one's understanding of interaction webs and mutualism. Properties such as symmetry, strength and effectiveness have dimensions which may yield metrics for the other two categories. In and of itself, this category may not provide any startling insights, but information in the code memos should add to understanding of the other categories.

Coder	John Reap	Date	1/23/2008
Type	Theoretical Memo		
Category	Succession		
Title	?		

In ecology, succession is directional and largely predictable ecosystem development. Ecosystems begin as barren or severely disrupted landscapes that proceed through multiple organism communities until reaching a static or dynamic climax configuration. E.P. Odum wrote prolifically on the topic and is a good source of information about succession.

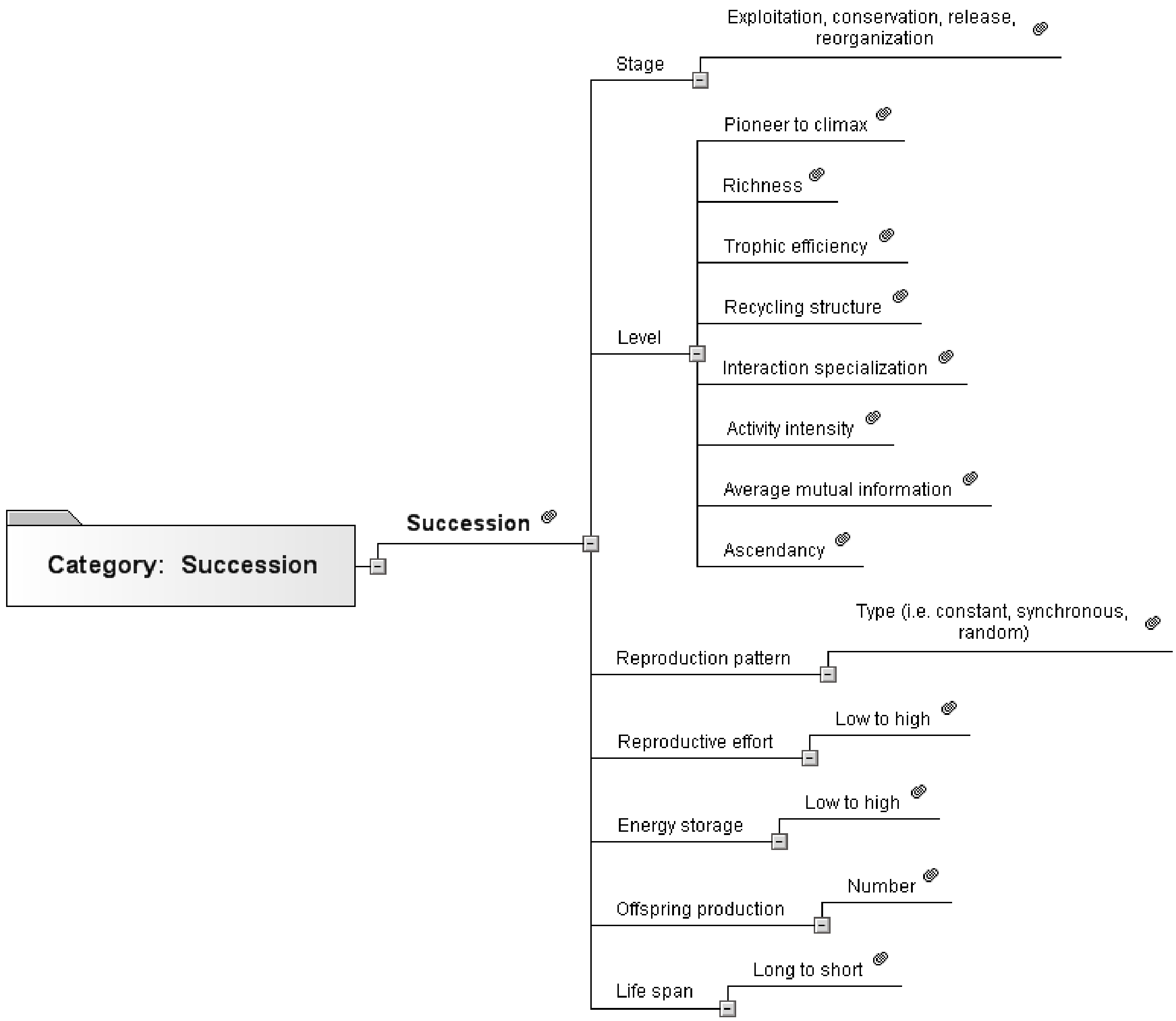


Figure 77: Succession Category with Properties and Dimensions

As coded, succession is a category with one rich concept (See Figure 65). Most of the properties are devoted to defining characteristics that allow one to differentiate different succession levels (i.e. pioneer, climax, etc.). Holling's stage property is an exception. It describes succession in terms of event-based time and represents the introduction of an idea markedly different than that of E.P. Odum and other authors. Holling's idea views climax succession as part of one of four cyclical ecosystem stages that proceed from exploitation to conservation to release to reorganization and back to exploitation.

Reconciling these divergent ideas within one sustainability principle based on ecosystem succession may not be possible. For the moment, it seems best to focus on ideas related to Odum's conception of succession.

The diagramed dimensions provide a number of opportunities for metric creation, and some, like Ulanowicz's ascendancy, are metrics. Climax ecosystems and those moving toward climax exhibit different dimensional values than pioneer ecosystems for the properties in Figure 65. It may, therefore, be possible to classify different types of industrial systems as pioneer, transitional or climax based on these metrics. The same metrics could guide design of industrial systems toward something closer to a climax configuration.

Such reasoning introduces two problems, though. First, not all biological systems reach or remain in a climax configuration. Second, one does not know if a climax industrial system is environmentally preferable. The latter problem is a matter for validation, but the former requires biological reasoning. If a number of ecosystems do not reach a climax, what can generally be said about succession? Can one even form a biological principle based on succession? If so, it seems likely that such a statement has already been formulated by Odum or his intellectual descendants. At this point, it seems best to build upon Odum's foundation by augmenting his findings with the result of the coding exercise.

Coder	John Reap	Date	2/14/2008
Type	Theoretical Memo		
Category	Succession		
Title	Measures and Metrics of Succession		

This memo further develops the Succession Category by defining metrics. Some metrics quantify dimensions in Figure 65. Others come from literature searches along the axis (or theme) of the category. E.P. Odum's comments contribute significantly to this latter group. Together, they quantify the succession phenomenon and represent a potential source of metrics for an associated sustainable engineering principle.

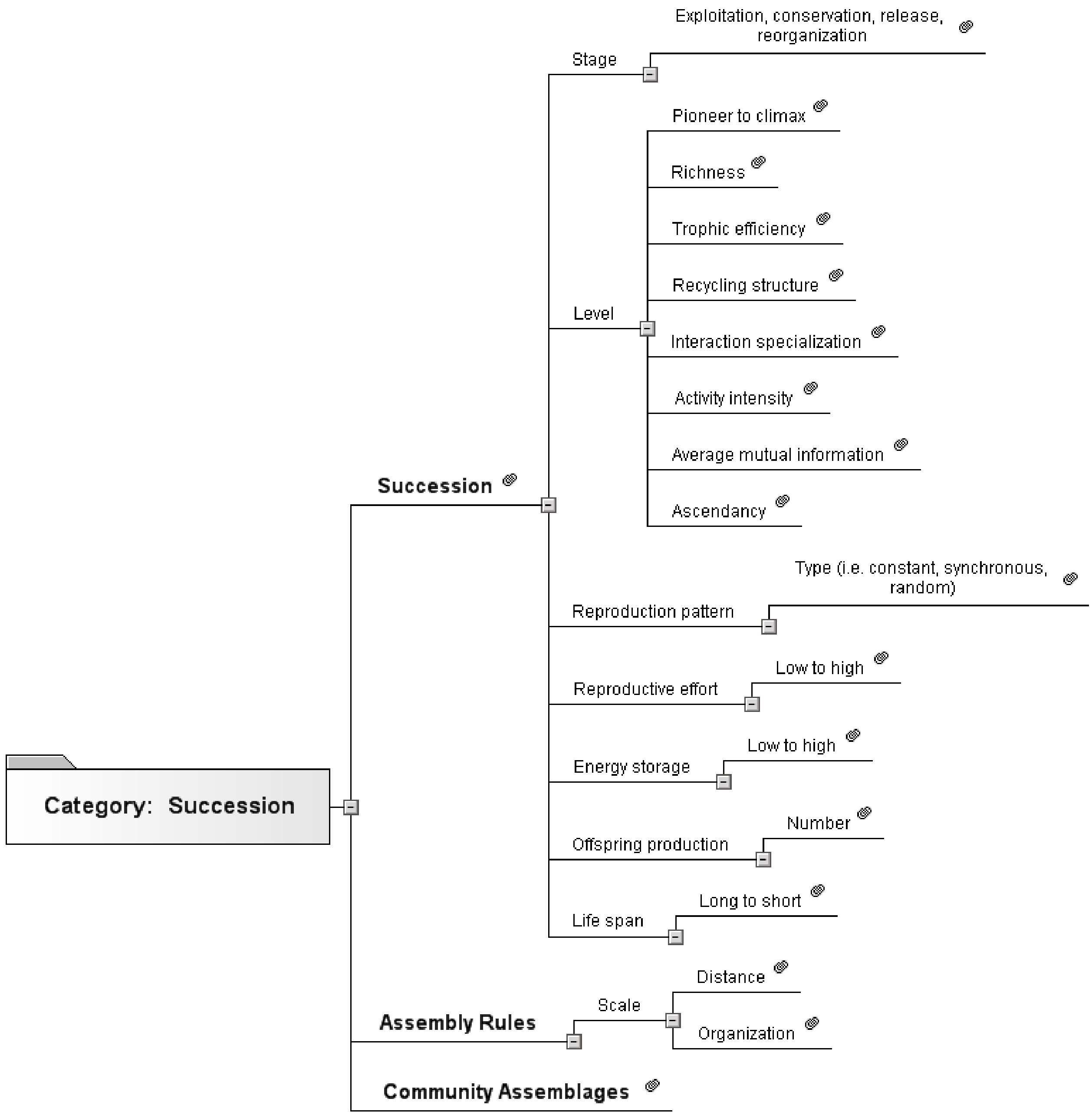


Figure 78: Succession Category with Properties and Dimensions

Most dimensions for the level property come from work by Ulanowicz. Interestingly, E.P. Odum's work with succession serves as the foundation for his work. Species richness refers to the number of species in an ecosystem. Dimensions such as trophic efficiency and recycling structure require more elaborate explanations. One calculates trophic efficiencies by determining the ratio of carbon reaching a top predator to the amount fixed by autotrophs at the base of a food web. Ulanowicz states that Leontief's I-O analysis provides an effective means of accomplishing this task; so, metrics advanced by Finn and Bailey can quantify this type of efficiency for ecosystems and industrial systems, respectively. Ulanowicz finds Finn's metrics for recycling structure inadequate (Ulanowicz 1996b). He proposes an approach that identifies number, length, and shared paths taken by material cycles in ecosystems (Ulanowicz 1983).

Average mutual information (I) is a metric drawn from information theory that Ulanowicz uses to quantify information about ecosystem behavior (Ulanowicz, et al. 1997).

$$I = k\sum_i \sum_j \left(\frac{T_{ij}}{T}\right)\log\left(\frac{T_{ij}T}{\sum_q T_{iq}\sum_r T_{rj}}\right)$$

In the equation for I, k is a scale factor, T_{ij} is the flow from compartment i to compartment j, and T is the sum of all trophic flows in the ecosystem. The term $\frac{T_{ij}}{\sum_q T_{iq}}$ is a conditional probability. He uses probability theory to quantify flows in ecosystems in an attempt to move the discipline away from purely mechanistic explanations for ecosystem behavior. Unfortunately, the remaining terms are not explained in his paper. Ascendancy (I) is simply Average mutual information scaled by the sum of ecosystem trophic flows; T replaces k when calculating A.

$$A = T\sum_i \sum_j \left(\frac{T_{ij}}{T}\right)\log\left(\frac{T_{ij}T}{\sum_q T_{iq}\sum_r T_{rj}}\right)$$

According to Ulanowicz, Ascendancy increases as succession proceeds (Ulanowicz, et al. 1997). The ascendancy metric captures sheer growth of an ecosystem using T and increased organization using the remainder of the function.

Despite having reviewed the base paper, it is unclear to me why one needs to include probabilities, especially conditional probabilities, when measuring ecosystem development. Calculation of the conditional probability component of this function also mystifies me. What is *q*, and where did *r* come from?

Newell's memo contains multiple properties for succession focused on reproduction and organism life history. Reproductive effort (E_R) is quantified as the ratio of dry reproductive biomass (B_R) to total dry biomass (B).

$$E_R = \frac{B_R}{B}$$

A similar ratio of root biomass (B_R) to total biomass estimates energy storage (E_S).

$$E_S = \frac{B_{root}}{B}$$

One readily quantifies offspring production and life span by counting the number of offspring produced and by measuring the average amount of time organisms live.

E.P. Odum made great contributions to ecology, and he crystallized, at least qualitatively, the succession concept. Figure 65 lists observed succession trends, and it contains potential metrics for those that seemed plausibly quantifiable.

Table 169: Odum's Succession Trends [gaps in numbering indicate omission of trends to supported by observation](Odum 1987)

#	Area of Study	Succession Trend	Metric
1	Energetics	Biomass, inorganic detritus both increase	B, ΔB
2		Gross production increase in primary	P [mass of biomass added in a period of time]
3		Net production decreases	
4		Respiration increases	R
5		Production to respiration ratio moves toward unity	$\frac{P}{R}$
6		Biomass to production ratio increases	$\frac{B}{P}$
7	Nutrient Cycling	Element cycles increasingly closed	I-O analysis
8		Increasing turnover time and storage of essential materials	
9		Cycling ratio increases	$\frac{recycle}{thruput}$
11	Species and Community Structure	Species composition changes	
12		Diversity-richness increases	
13		Diversity-evenness increases	
14		r-strategists replaced by K-strategists	
15		Life cycles increase in length and complexity	
16		Organism size and offspring size increase	

Coder	John Reap	Date	3/8/2007
Type	Theoretical Memo		

Theoretical notes and the memos that contain them seem to be reflections upon ideas noted in code notes. These notes might include comparisons, questions and even additional line-by-line coding. In this theoretical note, I attempt to reflect upon the main points contained in the first fifteen code memos. Specifically, I focus upon the concepts associated with connectivity.

Connections, flows of material and energy across these connections and the viability of communities appear in multiple biology articles. The diagram for Ebenman and coauthors' work provides a convenient means of organizing these ideas (See Figure 79).

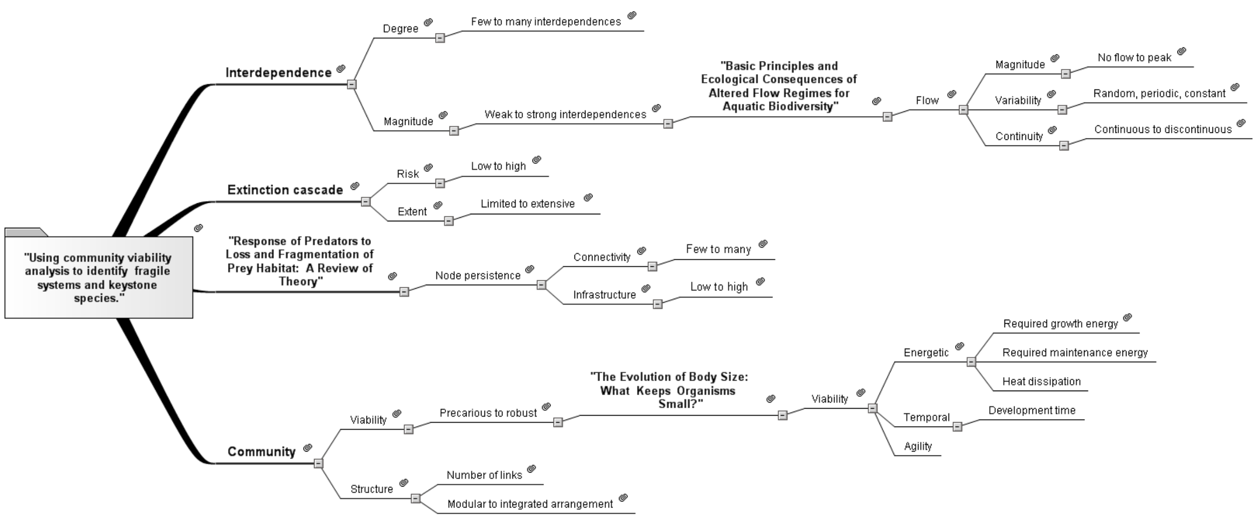


Figure 79: Connectivity Diagram

Ebenman's concept of interdependence as dimensioned by magnitude connects with concepts related to flow in Bunn's work. It seems reasonable that the strength of interdependence depends on energy and material flow magnitude, variability and continuity. One might hypothesize that the magnitude of interdependence (or dependence) increases as material and energy flow magnitude increases, continuity improves and variability declines. In other words, a large steady flow of material and energy leads to strong dependence or interdependence – a seemingly obvious statement.

Of course, this way of viewing a network is deeply rooted in the First Law of Thermodynamics; environmental analysis of this type must be well understood. A number of different quantities important to engineered and biological systems have been tracked. Material, energy, exergy and, to a lesser extent, energy have been modeled. If biology can offer anything to this type of analysis, it likely is in the form of targets, constraints and material types. It might also offer flow templates – particularly useful or common flow structures observed in nature. I might be able to explore these ideas within the context of Caroline's carpet recycling model.

Ebenman's concept of community as dimensioned by viability seems to connect with Blanckenhorn's concept of organism viability. After all, biological communities are assemblages of organisms! It seems reasonable to say that a community's viability can vary between precarious and robust in the same ways that its constituent organisms. Communities and organisms can move toward a precarious position by failing to obtain sufficient energy to maintain or grow. It should be noted that growth for an organism would represent a different type of maintenance for a community. This type of maintenance would have to do with replacement of a deceased adult. Time also helps describe community viability. Building conduits for material, energy and signal flows takes time. Periodic disruptions occurring at intervals shorter than the time needed to build such links effectively destroy communities. At the community level, agility is not simply defined; it might be a synonym for adaptability.

Finally, Ebenman's extinction cascade concept seems to be the negative of Ryall's node persistence concept. The ability of node's to persist represents the resistance to extinction or the resistance of a biological network to an extinction cascade. This is a useful thing to understand, but I suspect economic versions of this analysis have already been performed.

APPENDIX E

OPEN CODIND MEMOS FOR EBDM LITERATURE

This appendix contains open coding memos for EBDM literature. Each memo focuses on identification of terms know in Constant Comparative Method (CCM) as concepts, properties and dimensions. The contents of these memos aid in the validation of the bio-inspired sustainability guidelines stated in Chapter 3.

Coder	John Reap	Date	7/24/2008
Text Segment	Pages 3-4 and 8	Type	Memo
Reference	Abraham, M. A. (2006). Principles of Sustainable Engineering. Sustainability Science and Engineering: Defining Principles. M. A. Abraham. Boston, Elsevier. 1: 3-10.		

"…I…"

In this introductory chapter, four environmentally related concepts present themselves: resource minimization, substance hazard mitigation, life cycle and sustainability. The first two concepts receive the clearest treatment. Both factor prominently in the introductory discussion and the later list of principles. It is evident that the author is thinking about resource minimization properties such as efficiency and waste reduction; both have the dimensional ranges of low to high and material or energy. Hazard mitigation has properties of type and source. The type property seems focused on avoidance or treatment while the source of the hazard is either material or energy.

Life cycle has the property of stages which vary from resource extraction to end-of-life. Sustainability has the property of aspects which include social, economic and environmental.

Table 170: Summary of potential concepts, properties and dimensions for Abraham 2006

Concepts	Properties	Dimensions
Resource minimization	Efficiency	Low to high
		Material or energy
	Waste reduction	Low to high
		Material or energy
Substance hazard mitigation	Type	Avoidance, treatment
	Source	Energy or materials
Life cycle	Stages	Resource extraction to end-of-life
Sustainability	Aspects	Social, economic and environmental

Coder	John Reap	Date	10/7/2008
Text Segment	Article	Type	Memo
Reference	Allen, D. T. (2001). Chapter 3: Strategic Vision. WTEC Panel Report on Environmentally Benign Manufacturing. Baltimore, International Technology Research Institute: 23-29.		

Allen's article contains many of the concepts identified in previous coding exercises. These include: reuse, hazard avoidance, resource consumption reduction, and emissions reduction. He lists a number of environmentally benign manufacturing metrics. It is a telling indicator of the previous coding exercises' comprehensiveness that one may group almost all of the listed metrics under identified concepts.

Strategies for achieving most of these concepts are apparent. Reuse has strategies varying dimensionally from material recycling to product reuse. Hazard avoidance has toxic material reduction. Consumption reduction depends upon efficiency and product life extension. Consumption reduction also has the property of type which is either material or energy.

Table 171: Summary of potential concepts, properties and dimensions for Allen 2001

Concepts	Properties	Dimensions
Reuse	Strategy	Material recycling to product reuse
Resource consumption reduction	Strategy	Efficiency, product life extension
	Type	Material or energy
Emissions reduction	?	?
Hazard avoidance	Strategy	Toxic material reduction

Coder	John Reap	Date	10/5/2008
Text Segment	Page 51	Type	Memo
Reference	Allenby, B.R. (1999). Industrial Ecology: Policy Framework and Implementation. Upper Saddle River: Prentice Hall.		

"Products, processes…can produce residuals, but not waste."

Allenby presents 11 "principles" for industrial ecology in this short yet content full section. The first of these deals with emissions to the environment and, indirectly, resource reduction. Magnitude is one property of emissions that varies from low to high. One can also view his command to eliminate waste as a resource conservation strategy with the dimension of waste elimination.

His second principle is unique. It advocates preparedness for environmentally beneficial innovations. One might call this concept green readiness. While a general way of achieving this is not apparent, he does indicate that products, facilities and other works of engineering can have a low to high degree of green readiness.

Potential Concepts: emissions (P: magnitude D: low to high), resource reduction (P: strategy D: waste elimination), green readiness (P: degree D: low to high)

Text Segment	Page 52	Type	Memo

"Industries should make minimum use of materials and energy..."

The next three principles call for the reduction in resource use. They add the property of type, which varies dimensionally by material or energy, to the previously mentioned concept. They also add the strategy of efficiency.

The remaining principles on the page deal with hazard reduction and reuse. When discussing the hazard of toxic materials, the author advocates the strategy of substitution.

The reuse concept also has the strategy property which varies from material recycling to product reuse. Finally, one of the latter principles adds the strategy of product life extension to the resource reduction concept.

Potential Concepts: emissions (P: magnitude D: low to high), resource reduction (P: strategy D: waste elimination, efficiency; P: type D: energy or material), green readiness (P: degree D: low to high)

Table 172: Summary of potential concepts, properties and dimensions for Allenby 1999 #1

Concepts	Properties	Dimensions
Emission	Magnitude	Low to high
Resource reduction	Strategy	Waste elimination, efficiency, life extension
	Type	Energy or material
Green readiness	Degree	Low to high
Hazard reduction	Strategy	Substitution
Reuse	Strategy	Material recycling to product reuse

Coder	John Reap	Date	10/6/2008
Text Segment	Pages 70-71	Type	Memo
Reference	Allenby, B.R. (1999). Industrial Ecology: Policy Framework and Implementation. Upper Saddle River: Prentice Hall.		

"In the non-chemical manufacturing sectors…implementation of industrial ecology principles is generally captured under the rubric of DFE..."

This short section on design for environment limits this encompassing idea to the manufacturing sector, and oddly, it limits design considerations to the detail phase. He discusses this concept in terms of company policies and specific problems. Design or manufacture changes meant to alleviate specific environmental problems clearly fall under this heading, but he also argues that policy changes can precipitate design and manufacturing changes indirectly. This gives rise to two properties. Generality in DfE varies from entity wide to problem specific. A related property is approach, which varies from direct to indirect.

Potential Concepts: design for environment (P: generality D: entity wide to problem specific)

Table 173: Summary of potential concepts, properties and dimensions for Allenby 1999 #2

Concepts	Properties	Dimensions
Design for environment	Generality	Entity wide to problem specific
	Approach	Direct to indirect

Coder	John Reap	Date	10/7/2008
Text Segment	Pages 43-45	Type	Memo
Reference	Allenby, B.R. (1999). Industrial Ecology: Policy Framework and Implementation. Upper Saddle River: Prentice Hall.		

"…no economic activity should create waste, only residuals..."

Three concepts dominate this section of Allenby's text. Reuse, the first of these concepts, is the theme underlying his discussion about the three types of resource cycling systems. This discussion shows that reuse depends upon structures which vary from linear to cyclic, and it indicates that the property of specific trans-boundary flow measures the completeness of reuse. The common strategy property takes the form of the dimensions of material cycling to component remanufacture.

Emission reduction and hazard avoidance occur amidst the discussion about cyclic models and reuse strategies. The cited quote clearly shows the importance of emission reduction, and it indicates the author's preference for the strategy of waste elimination. Strategy is also a property of hazard avoidance; in this case, dissipative toxics avoidance is stated as one potential strategy.

Potential Concepts: reuse (P: structure D: linear to cyclic; P: specific trans-boundary flow D: low to high; P: strategy D: material cycling to component remanufacture), emission reduction (P: strategy D: waste elimination), hazard avoidance (P: strategy D: dissipative toxics avoidance)

Table 174: Summary of potential concepts, properties and dimensions for Allenby 1999 #3

Concepts	Properties	Dimensions
Reuse	Structure	Linear to cyclic
	Specific trans-boundary flow	Low to high
	Strategy	Material recycling to component remanufacture
Emissions avoidance	Strategy	Waste elimination
Hazard avoidance	Strategy	Dissipative toxics avoidance

Coder	John Reap	Date	7/22/2008
Text Segment	Page: 13	Type	Memo Pages 11-14
Reference	Anastas, P. T. and J. B. Zimmerman (2006). The Twelve Principles of Green Engineering as a Foundation for Sustainability. Sustainability Science and Engineering: Defining Principles. M. A. Abraham. Boston, Elsevier. 1: 11-32.		

"Table 2: The Twelve Principles of Green Engineering"

Table 2 lists the authors sustainability principles, and as one might expect, it contains the most of the major concepts in this first section of their second chapter. Hazard minimization has the property of type which is either material or energy. It also has strategy as a property which varies from avoidance to treatment. The resource minimization concept encompasses three principles; its properties of type and strategy are apparent. The two types are either mass or energy, and strategies include waste reduction, efficiency and abundant sources. The reuse concept also appears in three different principles. Its type property varies dimensionally from recycling to product reuse, and the idea of reuse on scales ranging from product to systems is evident.

Potential Concepts: Hazard minimization (P: type D: material or energy; P: strategy D: avoidance to treatment), resource minimization (P: type D: mass or energy; P: strategy D: waste reduction, efficiency and abundant sources), reuse (P: type D: recycling to product reuse; P: Scale D: product to systems)

Text Segment	Page: 13, para. 2	Type	Memo

"…Green Engineering needs to…takes into account: Life-cycle considerations, Multi-scale applications: e.g. products, processes and systems"

Here, the life cycle concept again emerges in the EBDM literature. This time it appears alongside the separate idea of scale. Life cycles have stages that vary from resource extraction to end-of-life. Scale seems to be a property of a number of other concepts; reuse serves as an example.

Potential Concepts: Hazard minimization (P: type D: material or energy; P: strategy D: avoidance to treatment), resource minimization (P: type D: mass or energy; P: strategy D: waste reduction, efficiency and abundant sources), reuse (P: type D: recycling to product reuse; P: Scale D: product to systems), life cycle (P: stage D: resource extraction to end-of-life)

Table 175: Summary of potential concepts, properties and dimensions for Anastas 2006 #1

Concepts	Properties	Dimensions
Hazard minimization	Type	Material or energy
	Strategy	Avoidance to treatment
Resource minimization	Type	Mass or energy
	Strategy	Waste reduction, efficiency and abundant sources
Reuse	Type	Recycling to product reuse
	Scale	Product to systems
Life cycle	Stage	Resource extraction to end-of-life

Coder	John Reap	Date	7/22/2008
Text Segment	Page: 14-16	Type	Memo Pages 14-16
Reference	Anastas, P. T. and J. B. Zimmerman (2006). The Twelve Principles of Green Engineering as a Foundation for Sustainability. Sustainability Science and Engineering: Defining Principles. M. A. Abraham. Boston, Elsevier. 1: 11-32.		

"…alternative approach is necessarily making your materials and chemicals as innocuous as possible."

This and all memos following Anastas_1 treat the major concepts identified by reviewing the authors' principle list in greater detail.

When discussing their first principle of green design, the authors focus on the concept of hazardous substance minimization. As discussed, it has the property of strategy. Strategy's dimension varies discretely to include avoidance or containment.

Potential Concepts: hazard substance minimization (P: strategy D: avoidance to containment)

Table 176: Summary of potential concepts, properties and dimensions for Anastas 2006 #2

Concepts	Properties	Dimensions
Hazard substance minimization	Strategy	Avoidance to containment

Coder	John Reap	Date	7/22/2008
Text Segment	Page: 17-18, 19-20, 24-26, 30-31	Type	Memo Pages
Reference	Anastas, P. T. and J. B. Zimmerman (2006). The Twelve Principles of Green Engineering as a Foundation for Sustainability. <u>Sustainability Science and Engineering: Defining Principles</u>. M. A. Abraham. Boston, Elsevier. 1: 11-32.		

Principles 2, 4, 7-8 and 12 deal with different aspects of the concept of <u>resource minimization</u>. The principles tend to define the dimensional range of its <u>strategy</u> property. Principle 2 discusses waste reduction while the Principle 4 emphasizes efficiency. Principle 12 emphasizes the use of abundant or renewable materials. Taken together, these principles create a dimensional range spanning <u>waste reduction, efficiency and abundance</u>. <u>Scale</u> is a property introduced by Principle 4. The authors mention efficiency at scales ranging from <u>product to system</u>.

Principles 7 and 8 present the strategy of waste reduction in a unique light. They draw attention to the fact that products might be designed to be intentionally wasteful to compensate for extreme, though unlikely, conditions. They illustrate that strategies interact with the property of <u>design phase</u> which varies from <u>requirements to manufacturing</u>. Using this coding construct, applying waste reduction strategy in the requirements phase eliminates the wastes of over-design.

Potential Concepts: resource minimization (P: strategy D: waste reduction, efficiency and abundance; P: scale D: product to system)

Table 177: Summary of potential concepts, properties and dimensions for Anastas 2006 #3

Concepts	Properties	Dimensions
resource minimization	strategy	Waste reduction, efficiency and abundance
	Scale	Product to system

Coder	John Reap	Date	7/22/2008
Text Segment	Page: 21	Type	Memo Pages
Reference	Anastas, P. T. and J. B. Zimmerman (2006). The Twelve Principles of Green Engineering as a Foundation for Sustainability. <u>Sustainability Science and Engineering: Defining Principles</u>. M. A. Abraham. Boston, Elsevier. 1: 11-32.		

"…Le Chartlier's Principle has been borne out in chemical…systems…is also a useful design tool generally for…other processes and systems."

Principle 5 is a version of Le Chartlier's Principle that focuses on the right or product side of an equation. The authors advise that resources will be more efficiently consumed if one allows demand to drive the production system. It is reasonable to think of this idea as another strategy for resource minimization, but unlike the others, this one is less technical and more managerial. One might call the concept <u>demand driven control</u>. The authors refer to its influence at multiple length scales; so, it clearly has the property of <u>scale</u> that varies from <u>molecular to systems</u>.

Potential Concepts: resource minimization (P: strategy D: waste reduction, efficiency and abundance; P: scale D: product to system)

Table 178: Summary of potential concepts, properties and dimensions for for Anastas 2006 #3

Concepts	Properties	Dimensions
Demand driven control	Scale	Molecule to system

Coder	John Reap	Date	7/25/2008
Text Segment	Page: 18-19	Type	Memo
Reference	Anastas, P. T. and J. B. Zimmerman (2006). The Twelve Principles of Green Engineering as a Foundation for Sustainability. Sustainability Science and Engineering: Defining Principles. M. A. Abraham. Boston, Elsevier. 1: 11-32.		

"Virtually every current manufacturing process will require a separation and purification step."

Principles 3, 6 and 9-10 present some aspect of the reuse concept. Principle 3's primary concept is separation which has properties of type and difficulty. Type has dimensions of atomic, chemical and mechanical. Difficulty seems to possess two sets of dimensions. The authors discuss the material and energy intensity of separation; so, it can range from low to high resource intensity. They also mention examples suggesting that difficulty ranges from automatic to manual. Separation is least environmentally burdensome when mechanical separation using few resources automatically occurs.

It is particularly noteworthy that the authors identify the Lotus-Effect as an "elegant design solution" to the problem of separation.

Potential Concepts: reuse, separation (P: type D: atomic, chemical and mechanical; P: difficulty D: low to high resource intensity, D: automatic to manual)

Text Segment	Page: 18-19	Type	Memo

"Based on what levels of energy, time and material has been invested, one can make generalizations about the proper way to handle the materials."

Principle 6 primarily adds the value property to the reuse concept. Value is measured in terms of complexity with dimensions such as low to high complexity.

Potential Concepts: reuse (P: value D: low to high complexity), separation (P: type D: atomic, chemical and mechanical; P: difficulty D: low to high resource intensity, D: automatic to manual)

Text Segment	Page: 26-28	Type	Memo

"Material diversity…determines the ease of disassembly for reuse and recycling."

Principle 6, 9 and 10 contain reuse strategies ranging from recycling to product reuse. However, there value lies in the identification of related properties and concepts that might enable reuse. Principle 9 discusses material diversity which varies from low to high. This is a property of reuse that determines the ease with which one can execute various reuse strategies. Principle 10 introduces the concept of system structure. Interconnectivity is a property of system structure that varies from low to high. It is interconnectivity that allows a material system to execute reuse strategies. Another property might be availability. In this context, availability refers to the capacity of a system to reuse a certain resource.

Potential Concepts: reuse (P: value D: low to high complexity; P: strategies D: recycling to product reuse; P: material diversity D: low to high), separation (P: type D: atomic, chemical and mechanical; P: difficulty D: low to high resource intensity, D:

automatic to manual), system structure (P: interconnectivity D: low to high; P: availability D: ?)

Table 179: Summary of potential concepts, properties and dimensions for Anastas 2006 #4

Concepts	Properties	Dimensions
Reuse	Value	Low to high complexity
	Strategy	Recycling to reuse
	Material diversity	Low to high
Separation	Type	Atomic, chemical and mechanical
	Difficulty	Low to high resource intensity
		Automatic to manual
System structure	Interconnectivity	Low to high
	Availability	Low to high

Coder	John Reap	Date	12/17/2008
Text Segment	Abstract	Type	Memo
Reference	Azapagic, A., A. Millington and A. Collett (2006). "A Methodology for Integrating Sustainability Considerations into Process Design." *Chemical Engineering Research and Design* 84(6): 439-452.		

"…this paper proposes a new methodology for integrating sustainability considerations…underpinned by life cycle thinking…"

The abstract introduces the authors' overarching concepts of <u>sustainability</u> and <u>life cycle</u>. Sustainability is introduced with the property of <u>components</u> which include <u>economic, environmental and social</u>.

Potential Concepts: sustainability (P: components D: economic, environmental and social), life cycle

Text Segment	Remainder of paper	Type	Memo

"Table 1: Examples of sustainability design criteria and indicators"

Table 1 contains the major concepts forming the core of the life cycle based design method proposed by the authors. It emphasizes <u>resource consumption</u>, <u>emissions</u> and <u>hazards</u>. The authors make a point of stating that the details of the application of these concepts depend upon the situation, and as a result, they largely refrain from providing any easily generalized depth in the form of properties and dimensions.

Potential Concepts: sustainability (P: consumption D: product to service), life cycle, resource consumption, emissions, hazards

Table 180: Summary of potential concepts, properties and dimensions for Azapagic 2006

Concepts	Properties	Dimensions
Life cycle	Phase	Cradle to grave
Sustainability	?	?
Resource consumption	?	?
Emissions	?	?
Hazards	?	?

Coder	John Reap	Date	7/30/2008
Text Segment	Abstract	Type	Memo
Reference	Baldwin, J.S., R. Murray, B. Winder and K. Ridgway. (2004). "A non-equilibrium thermodynamics model of industrial development: analogy or homology?" *Journal of Cleaner Production* 12: 841-853.		

"Homologous underlying processes and emergent patterns are hypothesized to be found between natural and industrial systems in…energy intensity, production…diversification…organizational life histories…homeostatis."

More a loose comparison of economic and industrial data to known ecosystem responses than a modeling exercise, this paper uses five central concepts drawn from Odum's ecosystem work as a unifying structure: energy intensity, reuse, diversity, organizational history, and homeostasis. Building a property-dimension structure for some of these concepts seems possible, but given their near direct transfer from biology, these structures would reflect themes in biology more than those in DfE. However, their appearance in this journal indicates that they have become themes in DfE. So, I will compromise position in this code memo by simply stating the concepts.

Potential Concepts: energy intensity, reuse, diversity, organizational history, homeostasis

Table 181: Summary of potential concepts, properties and dimensions for Baldwin 2004

Concepts	Properties	Dimensions
Energy intensity	?	?
Reuse	?	?
Diversity	?	?
Organizational history	?	?
Homeostasis	?	?

Coder	John Reap	Date	12/21/2008
Text Segment	Abstract	Type	Memo
Reference	Bergen, S. D., S. M. Bolton and J. L. Fridley (2001). "Design principles for ecological engineering." *Ecological Engineering* 18(2): 201-210.		

"(4) design for efficiency in energy and information…"

This paper's title suggests that one might encounter a number of guiding principles for EBDM. However the abstract only reveals a clear concern with <u>resource consumption</u> which is further defined by the property of <u>type</u> and <u>strategy</u> and is dimensioned by <u>energy</u> and <u>efficiency</u>, respectively.

Potential Concepts: resource consumption (P: type D: energy; P: strategy D: efficiency)

Text Segment	Para. 12-13	Type	Memo

"…integration of society and ecosystems in the built environment…"

Here, one sees the barest beginnings of a push away from purely philosophical ideas into a more concrete prescription for action in the physical world. The authors call for integration of the natural and man-made structures; they call for <u>bio-compatible</u> technology.

Potential Concepts: resource consumption (P: type D: energy; P: strategy D: efficiency), bio-compatible

Text Segment	Para. 15	Type	Memo

"…harvest some benefit from the ecosystem while preserving the health or integrity of the system…"

The author betrays a clear preference for renewable resources despite the surrounding philosophical discussion. Rate and natural fluctuation are key properties of renewable resources in his discussion. Rate varies dimensionally from below to beyond replacement, and fluctuation varies dimensionally from less to more than.

Potential Concepts: resource consumption (P: type D: energy; P: strategy D: efficiency), bio-compatible, renewable resources (P: rate D: below to beyond replacement; P: natural fluctuation D: less to more than)

Table 182: Summary of potential concepts, properties and dimensions for Bergen 2001

Concepts	Properties	Dimensions
Resource consumption	Type	Energy
	Strategy	Efficiency
Bio compatibility	?	?
Renewable resources	Rate	Below to beyond replacement
	Natural fluctuation	Less to more than

Coder	John Reap	Date	7/15/2008
Text Segment	Paragraphs 1-6, 18-end	Type	Memo
Reference	Brady, T. and T. McManus (2003) "Design for Environment at Intel" *Proceedings of EcoDesign2003: Third Inter. Symp. On Environmentally Conscious Design and Inverse Manufacturing*, Tokyo, Japan, December 8-11.		

"We strive to conserve natural resources and reduce the environmental burdens of waster generation and…be leaders in reducing, reusing and recycling..."

This article discusses Intel's objectives and achievements in design for the environment. As the quoted passage indicates, their main focus is on <u>reuse</u> and <u>resource minimization</u>. Reuse's property of <u>type</u> seems confined to <u>recycling</u>. Resource minimization has the property of <u>efficiency</u> which varies from <u>technology development to process improvement</u>. This variation represents a greater range than other articles. Most others confine themselves to product or process improvement. Efficiency also varies by <u>material or energy</u>. Energy efficiency is a key focus for products while material efficiency seems more of a manufacturing focus.

Potential Concepts: reuse (P: type D: recycling), resource minimization (P: efficiency D: technology development to process improvement, D: material or energy)

Text Segment	Paragraph: 8-14	Type	Memo

"…material content of electronic products, in particular heavy metals...has been at the forefront of many electronic companies..."

<u>Material</u> is another important concept in this article. Material's <u>hazard</u> property is of particular interest in this context. It varies dimensionally from <u>benign to toxic</u>, and the

authors spend a number of paragraphs detailing Intel's efforts to reduce the use of toxic materials and communicate hazard information pertaining to their products.

Potential Concepts: material (P: hazard D: benign to toxic)

Table 183: Summary of potential concepts, properties and dimensions for Brady 2003

Concepts	Properties	Dimensions
Reuse	Type	Recycling
Resource minimization	Efficiency	Material or energy
		Technology to process improvement
Material	Hazard	Benign to toxic

Coder	John Reap	Date	11/16/2008
Text Segment	Pages 3	Type	Memo
Reference	Byggeth, S., G. Broman and K.-H. Robèrt (2007). "A method for sustainable product development based on a modular system of guiding questions." *Journal of Cleaner Production* 15(1): 1-11.		

"In the sustainable society, nature is not subject to systematically increasing…Concentrations of substances...from the Earth's crust…produced by society. Degradation by physical means."

The author's primary objective is to layout a method for sustainable product design. However, what serves as the method's foundation? The answer comes on the third page when she lists the Natural Step Principles. The first two refer to the <u>emissions</u> concept and reveal its property of <u>source</u> which discretely varies between <u>Earth and society</u>. Degradation of physical means might refer to ecosystem decline; the means of producing ecosystem goods and services would decline as ecosystems declined. The third principle, therefore, refers to <u>biological integrity</u>. It might also generally refer to <u>resource consumption</u>.

Potential Concepts: emissions (P: source D: Earth and society), biological integrity, resource consumption

Text Segment	Page 4	Type	Memo

"…principles imply that materials…integrate into natural material cycles within ecosphere or…integrate into essentially closed material cycles within the technosphere."

The author's explanation of the principles reveals other interpretations that lead to still more concepts. The idea of integrating into biological cycles is a reference to the <u>biocompatibility</u> concept. This concept is specifically described by the <u>strategy</u> of biodegradability. Technosphere based material loops are a reference to reuse via the strategy of recycling.

The explanation yields properties for previously encountered concepts as well. The author notes the importance of the basic resource types – material or energy. Rate is observed to be an important property for emissions, which varies from low to high and from below to beyond assimilative capacity.

Potential Concepts: emissions (P: source D: Earth and society; P: rate D: low to high, below to beyond assimilative capacity), biological integrity, resource consumption (P: type D: material to energy), biocompatibility (P: strategy D: biodegradability), reuse (P: strategy D: recycling)

Text Segment	Page 5	Type	Memo

The fifth page contains a table of questions meant to aid designers assessing the sustainability of their product design decisions. It largely serves to add the strategy property to the identified concepts of resource consumption, emissions and biocompatibility. Efficiency is seen as a strategy for reducing emissions and consumption. Renewables can be viewed as another strategy for reducing resource consumption. Use of abundant metals is seen as a means of achieving better biocompatibility.

Potential Concepts: emissions (P: source D: Earth and society; P: rate D: low to high, below to beyond assimilative capacity; P: strategy D: efficiency), biological integrity, resource consumption (P: type D: material to energy; P: strategy D: efficiency, renewables), biocompatibility (P: strategy D: biodegradability, abundant metals), reuse (P: strategy D: recycling)

Table 184: Summary of potential concepts, properties and dimensions for Byggeth 2007

Concepts	Properties	Dimensions
Reuse	Strategy	Recycling
Biocompatibility	Strategy	Biodegradability
		Abundant metals
Nutrient	Type	Biological or technical
	Safety	Dangerous to safe
Biological integrity	?	?
Resource consumption	Strategy	Efficiency
		Renewables
	Type	Energy or material
Emissions	Source	Earth or society
	Rate	Low to high
		Below to beyond assimilative capacity
	Strategy	Efficiency

Coder	John Reap	Date	12/17/2008
Text Segment	Article	Type	Memo
Reference	Chen, J. L. and C.-C. Liu (2001). "An eco-innovative design approach incorporating the TRIZ method without contradiction analysis." *The Journal of Sustainable Product Design* 1: 263-272.		

The paper attempts to adapt TRIZ techniques to support DfE. The DfE core of the work appears early in the paper and focuses on concepts such as resource consumption reduction, toxic reduction, reuse and renewable resources. Resource consumption has properties of type and strategy which respectively vary between material or energy and recycling.

Table 185: Summary of potential concepts, properties and dimensions for Chen 2001

Concepts	Properties	Dimensions
Resource consumption reduction	Type	Material or energy
	Strategy	Recycling
Toxic reduction	?	?
Reuse	?	?
Renewable resources	?	?

Coder	John Reap	Date	12/21/2008
Text Segment	Abstract	Type	Memo
Reference	Clift, R. (2007). "Climate change and energy policy: The importance of sustainability arguments." *Energy* 32(4): 262-268.		

"…limits on emissions…achieved economically if the efficiency of energy use is improved to achieve reduction in demand…"

Clift's abstract reveals concern with emissions and resource consumption. The strategy property for resource consumption is evident in his selection of efficiency.

Potential Concepts: emissions, resource consumption (P: strategy D: efficiency)

Text Segment	Para. 4-6	Type	Memo

"…capacity of the biosphere to absorb or adapt to the emissions from human activities…"

His statements about absorption capacity lead me to think about emission severity. Regardless of the type or level of emission, the response of the biosphere to the emission determines its impact. Severity, then, may be the most appropriate label for the property dimensioned by below to beyond capacity.

Potential Concepts: emissions (P: severity D: below to beyond capacity), resource consumption (P: strategy D: efficiency)

Table 186: Summary of potential concepts, properties and dimensions for Clift 2007

Concepts	Properties	Dimensions
Emissions	Severity	Below to beyond capacity
Resource consumption	Strategy	Efficiency

Coder	John Reap	Date	7/30/2008
Text Segment	Abstract – para. 1	Type	Memo
Reference	Cooper, Joyce S. (2007). "Evolution of an Interdisciplinary Course in Sustainability and Design for Environment" *International Journal of Engineering Education* 23(2): 294-300.		

"…Sustainability describes…development…that meet the needs of the present while sustaining the qualities…that future generations may need..."

Sustainability is a context providing concept in this paper about a course at the University of Washington. Related concepts for which the paper provides more information include resource reduction and reuse. The authors seem to argue that achieving sustainability involves implementing a number of strategies such as conservation, efficiency and waste minimization. These strategies apply to the two types of resources: material and energy. Reuse strategies such as refurbishment and recycling are also discussed.

The remainder of the text describes class design, changes and impacts. It does not provide further information about sustainability or DfE guidance.

Potential Concepts: sustainability, resource reduction (P: strategies D: conservation, efficiency and waste minimization; P: type D: material or energy), reuse (P: strategy D: product refurbishment and recycling)

Table 187: Summary of potential concepts, properties and dimensions for Cooper 2007

Concepts	Properties	Dimensions
Resource reduction	Strategies	Conservation, efficiency waste minimization
	Type	Material or energy
Sustainability	?	?
Reuse	Strategy	Product refurbishment and recycling

Coder	John Reap	Date	12/17/2008
Text Segment	Abstract – para. 4	Type	Memo
Reference	Dewulf, J. and H. Van Langenhove (2005). "Integrating industrial ecology principles into a set of environmental sustainability indicators for technology assessment." *Resources, Conservation and Recycling* 43(4): 419-432.		

"The indicators…take into account: (1) renewability of resources; (2) toxicity of emissions; (3) input of used materials; (4) recoverability of products…; (5) process efficiency."

The abstract covers the main concepts of renewable resources, hazard avoidance, resource consumption, reuse and emissions encountered in many other EBDM papers. Process efficiency appears next to the main concepts, but it is a strategy for reducing resource consumption.

As one might expect, the sustainability concept also appears early in the paper.

Potential Concepts: renewable resources, hazard avoidance, resource consumption (P: strategies D: efficiency), reuse, emissions

Text Segment	Para. 6-8	Type	Memo

"…recoverability of the generated materials at end of their use…"

Here the discussion of metrics adds a property to reuse. Recoverability can be seen to vary dimensionally from low to high.

Potential Concepts: renewable resources, hazard avoidance, resource consumption (P: strategies D: efficiency), reuse (P: recoverability D: low to high), emissions

Text Segment	Para. 15-19	**Type**	Memo

These paragraphs contain the core of the authors' contribution to the concepts mentioned in the abstract. They provide exergetic metrics for resource consumption, reuse, renewable resources and hazard avoidance. One might say they define the property of <u>level</u> for each and dimension each level with <u>low to high exergetic ratio</u>.

Potential Concepts: renewable resources (P: level D: low to high exergetic ratio), hazard avoidance (P: level D: low to high exergetic ratio), resource consumption (P: strategies D: efficiency; P: level D: low to high exergetic ratio), reuse (P: recoverability D: low to high; P: level D: low to high exergetic ratio), emissions (P: level D: low to high exergetic ratio)

Table 188: Summary of potential concepts, properties and dimensions Dewulf 2005

Concepts	Properties	Dimensions
Renewable resources	Level	Low to high exergetic ratio
Hazard avoidance	Level	Low to high exergetic ratio
Resource consumption	Strategies	Efficiency
	Level	Low to high exergetic ratio
Reuse	Recoverability	Low to high
	Level	Low to high exergetic ratio
Emissions	Level	Low to high exergetic ratio

Coder	John Reap	Date	12/21/2008
Text Segment	Figure 1	Type	Memo
Reference	Eckelman, M. J., J. B. Zimmerman and P. T. Anastas (2008). "Toward Green Nano." *Journal of Industrial Ecology* 12(3): 316-328.		

"Summary of the principles of green chemistry and green engineering"

Many of the concepts, properties and dimensions encountered in this paper are summarized in its first figure. One sees concern with emissions and hazard reduction and resource consumption. In terms of hazard reduction, listed strategies include substance substitution and process substitution. Resource consumption strategies include efficiency and durability. Other important concepts are reuse, renewable resources and bio-compatibility. Important properties affecting reuse include material number and separability, and both vary dimensionally from low to high. Interestingly, the authors also believe that material and information flow bundling is important for enhancing EBDM.

Potential Concepts: Emissions, hazard reduction (P: strategy D: substance substitution, process substitution), resource consumption (P: strategies D: efficiency, durability), reuse (P: material number D: low to high; P: separability D: low to high), renewable resources, bio-compatibility, material and information flow bundling

Text Segment	Page 322	Type	Memo

Here the author differentiates between theoretical and realized efficiencies.

Potential Concepts: Emissions, hazard reduction (P: strategy D: substance substitution, process substitution), resource consumption (P: strategies D: theoretical efficiency, realized efficiency, durability), reuse (P: material number D: low to high; P: separability D: low to high), renewable resources, bio-compatibility, material and information flow bundling

Table 189: Summary of potential concepts, properties and dimensions for Eckelman 2008

Concepts	Properties	Dimensions
Emissions	?	?
Hazard reduction	Strategy	Substance substitution
		Process substitution
Resource consumption	Strategies	Theoretical efficiency
		Realized efficiency
		Durability
Reuse	Material number	Low to high
	Separation potential	Low to high
Renewable resources	?	?
Bio-compatibility	?	?
Material information flow bundling	?	?

Coder	John Reap	Date	9/8/2008
Text Segment	Abstract – Para. 3	Type	Memo
Reference	Ehrenfeld, J. and N. Gertler. (1997) "Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg" *Journal of Industrial Ecology* 1(1): 67-79.		

"…exchange of wastes, by-products, and energy among closely situated firms is…an 'industrial ecosystem' or 'industrial symbiosis'..."

Resource reduction and reuse are the concepts at the heart of the abstract. The by-product exchange is a strategy for achieving this goal. One can also see that different types of resources are discussed, and they can be dimensioned as either material or energy resources.

Potential Concepts: resource reduction (P: type D: material or energy), reuse (P: strategy D: by-product exchange; P: type D: material or energy)

Text Segment	Para. 4 - 7	Type	Memo

"…cascading use of energy and the use of industrial by products for processes other than the ones that created them..."

This section begins by providing another reuse strategy - energy cascades. Discussion of linkages between firms confirms the existence of the infrastructure property for reuse, and it provides the dimension of link number. In this sense infrastructure refers to the connections between companies executing material and energy exchanges and cascades.

Entropy enters the set of concepts present in this article in this section. They focus on the production rate property that varies from low to high. The authors concern themselves with possible links between entropy production rates and reuse infrastructure.

Connecting entropy and reuse, they hypothesize that low entropy production rates correspond with highly linked reuse infrastructure executing many by-product exchanges and energy cascades. They seem to believe that minimization of entropy production rate will necessitate formation of highly linked structures.

Potential Concepts: resource reduction (P: type D: material or energy), reuse (P: strategy D: by-product exchange, energy cascades; P: type D: material or energy; P: infrastructure D: link number), entropy (P: production rate D: low to high)

Table 190: Summary of potential concepts, properties and dimensions for Ehrenfeld 1997

Concepts	Properties	Dimensions
Reuse	Strategy	By-product exchange, energy cascade
	Types	Material or energy
	Infrastructure	Link number
Resource reduction	Types	Material or energy
Entropy	Production rate	Low to high

Coder	John Reap	Date	12/20/2008
Text Segment	Article	Type	Memo
Reference	Ehrenfeld, J. R. (2007). "Would Industrial Ecology Exist without Sustainability in the Background?" *Journal of Industrial Ecology* 11(1): 73-84.		

Ehrenfeld's largely philosophical discussion contains little in the way of physical guidance about the concept of sustainability. He seems to add the vague property of vitality to the concept, and he believes a sustainable system would "flourish" or exhibit a high degree of vitality. This suggests a dimensions ranging from low to high.

Potential Concepts: sustainability (P: vitality D: low to high)

Table 191: Summary of potential concepts, properties and dimensions for Ehrenfeld 2007

Concepts	Properties	Dimensions
Sustainability	Vitality	Low to high

Coder	John Reap	Date	12/21/2008
Text Segment	Abstract – para. 10	Type	Memo
Reference	Fang, Y., R. P. Côté and R. Qin (2007). "Industrial sustainability in China: Practice and prospects for eco-industrial development." *Journal of Environmental Management* 83(3): 315-328.		

"…closed loops involving chains and industrial symbiotic webs are the…core of successful initiatives in the application of industrial ecology."

The abstract mentions two concepts central to the remainder of the paper: resource consumption and reuse. Consumption is stated as the main impetus for the article and a central problem for China. Reuse, on the other hand, is stated in the context of closed loops and symbiotic webs, revealing the property of structure that varies dimensionally from linear to cyclic.

Potential Concepts: resource consumption, reuse (P: structure D: linear to cyclic)

Text Segment	Para. 14-22	**Type**	Memo

"…a coordinated effort to gain social, economic and ecological benefits through by-product and waste exchanges…"

In this set of paragraphs, the authors add depth to their reuse related ideas by adding strategies such as a by-product exchange, material recycling to product reuse. The remainder of the paper provides examples of the concepts and properties present in the first few pages.

Potential Concepts: resource consumption, reuse (P: structure D: linear to cyclic; P: strategies D: by-product exchange, material recycling to product reuse)

Table 192: Summary of potential concepts, properties and dimensions for Fang 2007

Concepts	Properties	Dimensions
Resource consumption	?	?
Reuse	Structure	Linear to cyclic
	Strategies	By-product exchange
		Material recycling to product reuse

Coder	John Reap	Date	7/15/2008
Text Segment	Paragraph: Abstract	Type	Memo
Reference	Fargnoli, Mario (2003) "The Assessment of the Environmental Sustainability" *Proceedings of EcoDesign2003: Third Inter. Symp. On Environmentally Conscious Design and Inverse Manufacturing*, Tokyo, Japan, December 8-11.		

"…benefits of making 'green' decisions in the early stages of the product design can be substantial."

Not surprisingly for an article in a design conference, the design decision concept appears early in the text and provides context for following discussions. The properties of interest mentioned in abstract include timing which varies from early to late and information content which varies from high to low. The author argues that increasing the amount of environmentally relevant information early in the decision process moves designs toward environmental sustainability.

Tool integration emerges from the author's discussion of solutions to the problem of informing early design decisions of environmental relevance. The primary property assigned to this concept is coverage. Coverage dimensionally ranges from cradle to grave and from single to all environmental effects.

Potential Concepts: design decision (P: timing D: early to late; P: information content D: low to high), tool integration (P: coverage D: cradle to grave, D: single to all environmental effects)

Text Segment	Paragraph: 5-	Type	Memo

"…valuation of the whole life cycle of the product is necessary, from raw material acquisition, through production, use and disposal..."

The most prominent concept in these paragraphs is life cycle. Much like tool integration, the property of coverage, with the dimension of cradle to grave, gives meaning to the concept. It is clear that the author believes any successful integrated tool should match the coverage usually achieved when analyzing product life cycles.

The paragraphs also contain multiple statements describing the type of design changes that reduce environmental effects. They focus on concepts such as reuse and resource minimization. Reuse has the property of type which varies from recycling to component remanufacture. Resource minimization has properties of avoidance which varies from product or process improvement and efficiency which has dimensions of mass or energy and product or process improvement.

Potential Concepts: design decision (P: timing D: early to late; P: information content D: low to high), tool integration (P: coverage D: cradle to grave, D: single to all environmental effects), life cycle (P: coverage D: cradle to grave), reuse (P: type D: recycling to component remanufacture), resource minimization (P: avoidance D: product or process improvement; P: efficiency D: mass or energy, D: product or process improvement)

Table 193: Summary of potential concepts, properties and dimensions for Fargnoli 2003

Concepts	Properties	Dimensions
Design decision	Timing	Early to late
	Information content	Low to high
Tool integration	Coverage	Cradle to grave
		Single to al environmental effects
Life cycle	Coverage	Cradle to grave
Reuse	Type	Recycling to component remanufacture
Resource minimization	Avoidance	Product to process improvement
	Efficiency	Mass or energy
		Product or process improvement

Coder	John Reap	Date	7/29/2008
Text Segment	Article	Type	Memo
Reference	Ferrao, P., P. Nazareth and Jose Amaral (2006). "Strategies for Meeting EU End-of-Life Vehicle Reuse/Recovery Targets" *Journal of Industrial Ecology* 10(4): 77-93.		

"…reuse and recovery rates for end-of-life vehicles are the subject of a recent European Union directive on ELVs..."

Reuse by the strategy of recycling dominates the authors' presentation. Energy recovery and component reuse also are seen as reuse strategies. Completeness and separation are properties of reuse given significant amounts of area in the paper, and they vary dimensionally from partial to complete and easy to difficult, respectively.

Potential Concepts: reuse (P: strategy D: recycling; P: completeness D: partial to complete; P: separation D: easy to difficult)

Table 194: Summary of potential concepts, properties and dimensions for Ferrao 2006

Concepts	Properties	Dimensions
Reuse	Strategy	Energy recovery to component reuse
	Separation	Easy to difficult
	Completeness	Partial to complete

Coder	John Reap	Date	11/8/2008
Text Segment	Article	Type	Memo
Reference	Fiksel, Joseph (2003). "Designing Resilient, Sustainable Systems" *Environmental Science and Technology* 37: 5330-5339.		

"…design systems with inherent 'resilience' by taking advantage of fundamental properties such as diversity, efficiency, adaptability, and cohesion."

The authors wide ranging paper touches on most of the common concepts found in EBDM literature. He mentions <u>resource consumption</u>, <u>emission reduction</u>, <u>hazard reduction</u> and <u>reuse</u> in multiple sections. Overarching concepts such as <u>sustainability</u> and <u>life cycle</u> are present throughout.

He does, however, present and define a concept not commonly found in other EBDM literature. The author devotes a number of sections to the <u>resilience</u> concept. As the quote indicates, he believes resilience has properties of <u>diversity</u>, <u>efficiency</u>, <u>adaptability</u> and <u>cohesion</u>. Each can vary dimensionally from <u>high to low</u> and from <u>small to large scale</u>. He equates sustainable engineering with engineering for resilience, and consequently, he believes that highly diverse, efficient, adaptable and cohesive systems manifesting these properties across multiple scales are more sustainable.

Table 195: Summary of potential concepts, properties and dimensions for Fiksel 2003 #1

Concepts	Properties	Dimensions
Resource consumption	?	?
Hazardous reduction	?	?
Emission reduction	?	?
Reuse	?	?
Sustainability	?	?
Life cycle	?	?
Resilience	Diversity	Low to high
		Small to large scale
	Efficiency	Low to high
		Small to large scale
	Adaptability	Low to high
		Small to large scale
	Cohesion	Low to high
		Small to large scale

Coder	John Reap	Date	12/??/2008
Text Segment	Abstract – para. 3	Type	Memo
Reference	Fiksel, J. (2003). "Designing Resilient, Sustainable Systems." *Environ. Sci. Technol.* 37(23): 5330-5339.		

"…design teams today must consider a broad range of system-level issues, including…material and energy efficiency, end-of-life recovery, environmental emissions…"

Though focused on resilience, the main concepts clearly evident in the introductory paragraphs are resource consumption, reuse and emissions. Properties of type and strategy for resource consumption are made evident by statements about their respective dimensions of energy or material and efficiency. Mention of end-of-life recovery introduces emissions, and the importance of emissions is clearly evident in the included quotation.

Potential Concepts: resource consumption (P: type D: energy or materials; P: strategy D: efficiency), reuse, emissions

Text Segment	Para. 9-13	Type	Memo

"…following definitions offer a logical framework of 'nested' systems…"

The nested definitions represent a property of the sustainability concept. This property of organizational scale varies dimensionally from product to society.

Potential Concepts: resource consumption (P: type D: energy or materials; P: strategy D: efficiency), reuse, emissions, sustainability (P: organizational scale D: product to society)

Text Segment	Para. 15-33	Type	Memo

"…the essence of sustainability is resilience."

In these paragraphs, the resilience concept comes to the fore. Here the author attaches properties of diversity, efficiency, adaptability, cohesion to the idea of resilience. Each can be thought to vary dimensionally from low to high, and the author believes a system grows more resilient as its level of these properties increases. He also notes the cyclical nature of efficient industrial networks. This observation introduces the property of structure which varies dimensionally from linear to cyclical to the reuse concept.

Potential Concepts: resource consumption (P: type D: energy or materials; P: strategy D: efficiency), reuse (P: structure D: linear to cyclical), emissions, sustainability (P: organizational scale D: product to society), resilience (P: diversity D: low to high; P: efficiency D: low to high; P: adaptability D: low to high; P: cohesion D: low to high)

Table 196: Summary of potential concepts, properties and dimensions for Fiksel 2003 #2

Concepts	Properties	Dimensions
Resource consumption	Type	Energy or materials
	Strategy	Efficiency
Reuse	Structure	Linear to cyclical
Emissions	?	?
Sustainability	Consumption	Product to service
Resilience	Diversity	Low to high
	Efficiency	Low to high
	Adaptability	Low to high
	Cohesion	Low to high

Coder	John Reap	Date	10/16/2008
Text Segment	Article	Type	Memo
Reference	Fitch, P.E., J.S. Cooper. (2004). "Life Cycle Energy Analysis as a Method for Material Selection" *Journal of Mechanical Design* 126: 798-804.		

"…paper presents a method of performing Life Cycle Energy Analysis (LCEA) for the purpose of material selection."

Life cycle and resource consumption are the dominant concepts in this article. Both appear in the quotation above and repeatedly appear in various forms throughout the article. Multiple equations constitute a method for calculating energy inputs for a products life cycle. They reveal that the life cycle concept has the property of phases which vary from material extraction to end-of-life. The properties associated with resource consumption are magnitude and type which vary dimensionally from low to high and by material or energy, respectively.

Potential Concepts: resource consumption (P: magnitude D: low to high; P: type D: material or energy), life cycle (P: phases D: material extraction to end-of-life)

Table 197: Summary of potential concepts, properties and dimensions for Fitch 2004

Concepts	Properties	Dimensions
Resource consumption	Magnitude	Low to high
	Type	Material or energy
Life cycle	Phases	Material extraction to end-of-life

Coder	John Reap	Date	8/22/2008
Text Segment	Abstract to page 9	Type	Memo
Reference	Garcia-Serna, J., L. Perez-Barrigon and M.J. Cocero (2007). New Trends for design toward sustainability in chemical engineering: Green Engineering. *Chemical Engineering Journal* 133: 7-30.		

"Today there are very few scientific, societal and political areas which have not been the subject of an examination based on sustainability criteria."

The abstract and opening statements introduce the overarching concept of sustainability as the article's theme. The related concept of scale appears alongside it, and the properties of organizational and temporal add to one's understanding of the scale concept. Organizational scale varies dimensionally from product to production systems while the temporal property varies from current generation to future generations.

After discussing scale's interaction with sustainability, the authors turn to the more traditional properties of sustainability: social, environmental and economic. Their dimensions respectively vary from united to anarchic, sustainable to decaying and from efficient to inefficient.

Potential concepts: sustainability (P: social D: united to anarchic; P: environmental D: sustainable to decaying; P: economic D: efficient to inefficient), scale (P: organizational D: product to production system; P: temporal D: current generation to future generations)

Text Segment	Page 10	Type	Memo

"…most products in which the process industries are concerned will pass through…extraction, transport, manufacture distribution, sale, utilization, disposal, recycling and final disposal."

While discussing ways to measure sustainability, the life cycle concept appears. Its extent property varies from cradle to grave.

Potential concepts: sustainability (P: social D: united to anarchic; P: environmental D: sustainable to decaying; P: economic D: efficient to inefficient), scale (P: organizational D: product to production system; P: temporal D: current generation to future generations), life cycle (P: extent D: cradle to grave)

Text Segment	Page 11-14	Type	Memo

"…System Conditions define what is required…to create prosperous businesses and a sustainable relationship with nature."

Though the cited quote comes from a section discussing The Natural Step (TNS), it summarizes the theme of these pages. Multiple concepts describing system conditions for sustainability emerge in this section. Cyclic economy is one such concept appearing in sections on The Natural Step, Biomimicry, zero waste and elsewhere. Solar power is a recurrent theme with the property of currency that varies dimensionally from present to past. The concept of Eco-foreign substances is another important addition. It has the property of concentration which varies from low to high. The natural integrity concept has properties of productivity and diversity which both vary dimensionally from high to low.

Concepts previously encountered in other coding exercises appear in this section as well. Renewable energy, resource reduction, material reuse and hazardous material reduction are recurring concepts. Resource reduction appears in the context of green chemistry. Its properties of energy and material both appear. The dimensions of both are efficiency, renewable sources and waste minimization. Material reuse has the property of type which varies from product reuse to recycling. Hazard reduction has the strategy property which has dimensions such as elimination, minimization, substitution, alternative reaction route and energy limitation.

Potential concepts: sustainability (P: social D: united to anarchic; P: environmental D: sustainable to decaying; P: economic D: efficient to inefficient), scale (P: organizational D: product to production system; P: temporal D: current generation to future generations), life cycle (P: extent D: cradle to grave), cyclic economy, eco-foreign substances (P: concentration D: low to high) natural integrity (P: productivity D: low to high; P: diversity D: low to high), renewable energy, material reuse (P: type D: product reuse to recycling), hazardous material reduction (P: strategy D: elimination, minimization, substitution, alternative reaction route and energy limitation), resource reduction (P: materials D: waste minimization, efficiency, renewable sources; P: energy D: Waste minimization, efficiency, renewable sources)

Text Segment	Page 19	Type	Memo

"…several characteristics are key for achieving the goal of sustainability."

Many established themes recur in this section. However, material reuse adds elements to its existing dimension. Namely, it adds component reuse and remanufacture. More importantly, the system resilience concept appears as a key sustainability characteristic.

Potential concepts: sustainability (P: social D: united to anarchic; P: environmental D: sustainable to decaying; P: economic D: efficient to inefficient), scale (P: organizational D: product to production system; P: temporal D: current generation to future generations), life cycle (P: extent D: cradle to grave), cyclic economy, eco-foreign substances (P: concentration D: low to high) natural integrity (P: productivity D: low to high; P: diversity D: low to high), renewable energy, material reuse (P: type D: product reuse to recycling), hazardous material reduction (P: strategy D: elimination, minimization, substitution, alternative reaction route and energy limitation), resource reduction (P: materials D: waste minimization, efficiency, renewable sources; P: energy D: Waste minimization, efficiency, renewable sources), system resilience

Text Segment	Page 20-end	Type	Memo

"…several characteristics are key for achieving the goal of sustainability."

Previously identified concepts repeatedly appear in different forms following page 19. The authors do make a distinction between resource reductions at different organizational scales. This adds the <u>scale</u> property which varies from <u>product to production system</u>. The also mention <u>carrying capacity</u>.

Potential concepts: sustainability (P: social D: united to anarchic; P: environmental D: sustainable to decaying; P: economic D: efficient to inefficient), scale (P: organizational D: product to production system; P: temporal D: current generation to future generations), life cycle (P: extent D: cradle to grave), cyclic economy, eco-foreign substances (P: concentration D: low to high) natural integrity (P: productivity D: low to high; P: diversity D: low to high), renewable energy, material reuse (P: type D: product reuse to recycling), hazardous material reduction (P: strategy D: elimination, minimization, substitution, alternative reaction route and energy limitation), resource reduction (P: materials D: waste minimization, efficiency, renewable sources; P: energy D: Waste minimization, efficiency, renewable sources; P: scale D: product to production system), system resilience

Table 198: Summary of potential concepts, properties and dimensions for Garcia-Serna 2007

Concepts	Properties	Dimensions
Sustainability	Social	United to anarchic
	Environmental	Sustainable to decaying
	Economic	Efficient to inefficient
Scale	Organizational	Product to production system
	Temporal	Current generation to future generations
Life cycle	Extent	Cradle to grave
Cyclic economy	?	?
Solar power	Currency	Present to past
Eco-foreign substances	Concentration	Low to high
Natural integrity	Productivity	Low to high
	Diversity	Low to high
Renewable energy	?	?
Resource reduction	Energy	Waste minimization, efficiency, renewable sources
	Material	Waste minimization, efficiency, renewable sources
	Scale	Product to production system
Material reuse	Type	Product reuse to recycling
Hazardous material reduction	Strategy	Elimination, minimization, substitution, alternative reaction route and energy limitation
System resilience	?	?
Carrying capacity	?	?

Coder	John Reap	Date	10/10/2008
Text Segment	Page 3-4, Para. 1-5	Type	Memo
Reference	Graedel, T.E. and B.R. Allenby (1996). Design for Environment. Upper Saddle River: Prentice Hall.		

"…industrial systems…will increasingly be under pressure to evolve from linear (Type I) to semicyclic (Type II) modes of operation."

In their section entitled a "Design for Environment: A Comprehensive Description," the authors devote at least half of their text to a concept description of a cyclic industrial economy. This idea is another form of the reuse concept. They describe Type 1 (linear) to Type III (cyclic) systems and state that humanity must move toward Type III industrial systems. Such statements indicate that reuse has the property of infrastructure which varies dimensionally from linear to cyclic.

Potential Concepts: reuse (P: structure D: linear to cyclic)

Text Segment	Page 6-7, Para. 6-end	Type	Memo

"…one can adopt as goals that every erg of energy used in manufacture should produce a desired material transformation, that every molecule that enters a specific manufacturing process leave as part of a saleable product."

The last paragraphs in the comprehensive review focus on the concept of resource reduction through the strategy of efficient production. The above cited statement also indicates that resource reduction has the property of type which possesses dimensions of material or energy.

Potential Concepts: reuse (P: structure D: linear to cyclic), resource reduction (P: strategy D: efficiency)

Table 199: Summary of potential concepts, properties and dimensions for Graedel 1996 #1

Concepts	Properties	Dimensions
Reuse	Structure	Linear to cyclic
Resource reduction	Strategy	Efficiency

Coder	John Reap	Date	10/13/2008
Text Segment	Page 105-111, Para. 1-13	Type	Memo
Reference	Graedel, T.E. and B.R. Allenby (1996). Design for Environment. Upper Saddle River: Prentice Hall.		

"…formal study of the environmental responsibility of a product is called life-cycle assessment (LCA). …flows of energy and materials to and from the product during its life are determined."

Three major concepts appear in the introduction to this section, and all three are apparent in the included quotation. The life cycle concept is clearly present. In fact, it influences the entire section. Resource consumption and Emissions are also present. The authors' statements about resource flows "to and from the products" reveal them. Resource consumption has the property of type which is dimensioned by material or energy.

Potential Concepts: life cycle, resource consumption (P: type D: material or energy), emissions

Text Segment	Page 113, Para. 14-18	**Type**	Memo

"…limit the use of toxic materials...optimize disassembly and reuse, either of modules (the preferable option) or materials."

The final paragraphs of this section bring two more concepts to the fore. Hazard avoidance in the guise of toxic material avoidance is the first to appear. Reuse appears in two contexts. The first mention of reuse appears with the strategy of marketable byproducts. The authors suggest designing processes in such a way as to fully utilize potential wastes. The second appearance is common to EBDM literature; the authors suggest reuse strategies that vary dimensionally from <u>materials recycling to assembly reuse</u>.

Potential Concepts: life cycle, resource consumption (P: type D: material or energy), emissions, reuse (P: strategy D: material recycling to assembly reuse, marketable byproducts), hazard avoidance

Table 200: Summary of potential concepts, properties and dimensions for Graedel 1996 #2

Concepts	Properties	Dimensions
Life cycle	?	?
Resource consumption	Type	Material or energy
Emissions	?	?
Reuse	Strategy	Material recycling to assembly reuse
		Marketable byproducts
Hazard avoidance	?	?

Coder	John Reap	Date	12/21/2008
Text Segment	Article	Type	Memo
Reference	Grenchus, E., R. Keene, C. Nobs, A. Brinkley, J. R. Kirby, D. Pitts and I. Wadehra (1998). Linking demanufacturing operations with product DFE initiatives. : Electronics and the Environment, 1998. ISEE-1998. Proceedings of the 1998 IEEE International Symposium on Oak Brook, IL, IEEE.		

Three concepts dominate this short article: reuse, resource consumption and emissions. The authors discuss aspects of the recycling strategy for reuse and a property of type for resource consumption. Emissions have the property of level which is dimensioned by low to high landfill utilization.

Table 201: Summary of potential concepts, properties and dimensions for Grenchus 1998

Concepts	Properties	Dimensions
Reuse	Strategy	Recycling
Resource consumption	Type	Energy
Emissions	Level	Low to high landfill utilization

Coder	John Reap	Date	10/9/2008
Text Segment	Para. 1-4	Type	Memo
Reference	Gutwoski, T. (2001). Polymers. WTEC Panel Report on Environmentally Benign Manufacturing. Baltimore, International Technology Research Institute: 53-62.		

"Polymers have a poor environmental image…due to their contribution to litter…hazardous air pollutants…and energy impacts."

The opening paragraph contains three established concepts in EBDM: emissions reduction, hazard reduction and reuse. The opening paragraphs provide the strategies of product reuse, recycling and incineration for the reuse concept.

Potential Concept: emissions reduction, hazard reduction, reuse (P: strategy D: incineration, recycling to product reuse)

Text Segment	Para. 5-13	Type	Memo

"A second important theme for polymers is energy reuse."

Pressing forward, one encounters discussions of mass and volume specific energy consumption for the production of polymers. The author makes a point of noting the impact of a 1% increase in process efficiency in the plastics industry. These occurrences are manifestations of a concern with resource consumption or, more precisely, with the resource consumption reduction concept. The citation points to this concepts type property which has dimensions of material or energy. Other statements about process efficiency and waste reduction point to the strategy property for resource and emissions reduction. Efficiency, materials substitution and materials exchange are dimensions for resource reduction's strategy property while waste reduction and waste recovery apply to both.

Potential Concept: emissions reduction (P: strategy D: waste reduction, waste recovery), hazard reduction, reuse (P: strategy D: incineration, recycling to product reuse), resource consumption reduction (P: type D: material and energy; P: strategy D: efficiency, materials substitution, materials exchange, waste reduction, waste recovery)

Text Segment	Page 59	Type	Memo

"The problem in most cases is related to infrastructure development and the reverse logistics process."

Specific examples or categories of examples for previously mentioned concepts dominate most of the remainder of the polymers section. However, the author repeatedly mentions the importance of infrastructure in relation to different kinds of polymer reuse. This indicates that infrastructure is a property of reuse. The citation reveals that the level of cycling, linear to cyclical, is an important dimension of infrastructure.

Potential Concept: emissions reduction (P: strategy D: waste reduction, waste recovery), hazard reduction, reuse (P: strategy D: incineration, recycling to product reuse; P: infrastructure D: linear to cyclical), resource consumption reduction (P: type D: material and energy; P: strategy D: efficiency, materials substitution, materials exchange, waste reduction, waste recovery)

Text Segment	Page 61	Type	Memo

"…most intriguing areas of new materials development is in the area of biomaterials...."

The primary idea in this section is development and use of materials that can biodegrade at the end of their useful lives. It is an effort to synchronize industrial material flows and cycles with naturally existing ones. So, this idea can be labeled with the concept of bio-synchronization.

Potential Concept: bio-synchronization, emissions reduction (P: strategy D: waste reduction, waste recovery), hazard reduction, reuse (P: strategy D: incineration, recycling to product reuse; P: infrastructure D: linear to cyclical), resource consumption reduction (P: type D: material and energy; P: strategy D: efficiency, materials substitution, materials exchange, waste reduction, waste recovery)

Table 202: Summary of potential concepts, properties and dimensions for Gutwoski 2001

Concepts	Properties	Dimensions
Emission reduction	Strategy	Waste reduction, waste recovery
Resource consumption reduction	Strategy	Efficiency, materials substitution, materials exchange, waste reduction, waste recovery
	Type	Energy or material
Reuse	Strategy	Incineration, material recycling to product reuse
	Infrastructure	Linear to cyclical
Hazard avoidance	Strategy	Substitution
Bio-synchronization	?	?

Coder	John Reap	Date	12/18/2008
Text Segment	Abstract – para. 3	Type	Memo
Reference	Harding, R. (2006). "Ecologically sustainable development: origins, implementation and challenges." *Desalination* 187(1-3): 229-239.		

"We seem unable to agree on *exactly* what sustainability means… What is clear, however, is that the way in which we use resources and deal with waste products requires urgent attention."

The cited quote shows the importance given by the author to the concepts of resource consumption and emissions. His surrounding statements clearly indicate that the less clear concept of sustainability is tied to these two in his mind.

Potential Concepts: resource consumption, emissions, sustainability

Text Segment	Para. 4-8	Type	Memo

"…resource consumption and waste assimilation requirements…defined…in terms of a corresponding productive land area."

In these paragraphs, one gains a property for emissions and resource use. Level as dimensioned by area provides insight into the degree of resource use and waste.

Potential Concepts: resource consumption (P: level D: area), emissions (P: level D: area), sustainability

Text Segment	Para. 9-11	Type	Memo

"…extent of de-materialization required – a factor of 10 or 90% in throughput of materials."

Here, one sees the author's advocacy for Factor 10 improvement in the use of resources. This is a version of the efficiency strategy for resource consumption reduction.

Potential Concepts: resource consumption (P: level D: area; P: strategies D: efficiency), emissions (P: level D: area), sustainability

Text Segment	Page 235	**Type**	Memo

"…four principles of ESD…conservation of biological diversity and ecological integrity..."

After spending much of the paper rehashing statements about resource consumption, waste and related policies and procedures, the author briefly returns his attention to physical guidelines. He states that ecological integrity should be conserved. It seems that one is to measure it using the property of biodiversity which may vary from low to high. Another reasonable interpretation is that both integrity and diversity are independent concepts.

Potential Concepts: resource consumption (P: level D: area; P: strategies D: efficiency), emissions (P: level D: area), sustainability, ecological integrity (P: biodiversity D: low to high)

Table 203: Summary of potential concepts, properties and dimensions for Harding 2006

Concepts	Properties	Dimensions
Sustainability	?	?
Resource consumption	Level	Area
	Strategies	Efficiency
Emissions	Level	Area
Ecological integrity	Biodiversity	Low to high

Coder	John Reap	Date	10/22/2008
Text Segment	Article	Type	Memo
Reference	Harper, S.R. and D.L. Thurston (2008). "Incorporating Environmental Impacts in Strategic Redesign of and Engineering System". *Journal of Mechanical Design* 130: 1-9.		

Though this article primarily deals with a design decision method, it is instructive to examine the authors' approach to incorporating environmental issues. Their interest in estimating environmental impacts over long time horizons and at different life cycle phases shows the importance of the life cycle concept in this work. Life cycles clearly have the property of phase which varies dimensionally from material extraction to decommissioning.

The considered life cycle impacts are also noteworthy. Utilized metrics include measures of emissions and toxicity of emissions. The use of these metrics indicates that the authors consider emission reduction and hazard reduction to be priorities in the design process.

Potential Concept: life cycle (P: phase D: material extraction to decommissioning), emission reduction, hazard reduction

Table 204: Summary of potential concepts, properties and dimensions for Harper 2008

Concepts	Properties	Dimensions
Emission reduction	?	?
Hazard reduction	?	?
Life cycle	Phase	Material extraction to decommissioning

Coder	John Reap	Date	12/18/2008
Text Segment	Abstract – para. 12	Type	Memo
Reference	Horn, D. A. and J. R. Mahanna (1999). Implementation of DfE at IBM - A Case Study on Network Server Products. Electronics and the Environment, 1999. ISEE -1999. Proceedings of the 1999 IEEE International Symposium on Danvers, MA, IEEE.		

"IBM Server Group has implemented…many principles of DfE, such as Design for Disassembly, recyclability, modularity, the use of recycled materials and power management."

As the abstract shows, a number of common EBDM concepts are mentioned or present in the form of examples in this short article. Concern with concepts such as reuse and resource consumption is clearly present in this article. Statements about recycling and disassembly reveal the presence of reuse's strategy property, where the strategies in question are recycling and remanufacture. Statements about power management indicate interest in resource consumption and reveal the associated property of type which is dimensioned by energy.

Proceeding further into the article, one sees unmistakable references to a desire to minimize resource consumption and hazards. The statement about resources adds material to the list of types. One also sees references to waste minimization as a strategy for consumption reduction. Hazard reduction refers to minimization of toxic material and dangerous processes. Strategies for hazard reduction include minimization and elimination.

Potential Concepts: reuse (P: strategies D: recycling, remanufacture), resource consumption (P: Type D: energy or material; P: strategies D: waste minimization), hazard reduction (P: strategy D: minimization, elimination)

Text Segment	Para. 13 - end	Type	Memo

"…key DfE criteria within the AS/400e series design encompasses energy efficiency."

Some examples of previously mentioned concepts reappear in the later parts of this article. Efficiency is added as strategy for reducing resource consumption.

Potential Concepts: reuse (P: strategies D: recycling, remanufacture), resource consumption (P: Type D: energy or material; P: strategies D: waste minimization, efficiency), hazard reduction (P: strategy D: minimization, elimination)

Table 205: Summary of potential concepts, properties and dimensions for Horn 1999

Concepts	Properties	Dimensions
Reuse	Strategies	Recycling, remanufacture
Resource consumption	Type	Energy or material
	Strategies	Waste min.
		Efficiency
Hazard reduction	Strategy	Minimization
		Elimination

Coder	John Reap	Date	7/25/2008
Text Segment	Article	Type	Memo
Reference	Huisman, J. and A. Stevels (2003). Balancing Design Strategies and End-of-Life Processing. Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, IEEE.		

"Reduce and replace…penalty elements and hazardous substance..."

The article describes QWERTY/EE (Quotes for environmentally WEighted RecyclabiliTY and Eco-Efficiency) and its application. This method revolves around three to four strategies for 1) reducing maximum avoided environmental damage, 2) reducing maximum possible damage and 3) maximizing realized avoided environmental damage. The first strategy counsels replacement and avoidance of hazardous substances. This is the concept of hazardous substance minimization with the property strategy dimensioned by efficiency and avoidance.

"Improve unlocking properties of parts…for shredding and separation as for disassembly..."

Two strategies deal with changing the physical relationships among materials in a part to improve recycling. They embody the concept of reuse, and they dimension its property of strategy as recycling to remanufacture. The separation concept appears as part of the latter two principles as well. Both principles recommend ways to reduce its property of difficulty which can vary from low to high.

Table 206: Summary of potential concepts, properties and dimensions for Huisman 2003

Concepts	Properties	Dimensions
Hazardous substance minimization	Strategy	Efficiency and avoidance
Reuse	Strategy	Recycling to remanufacture
Separation	Difficulty	Low to high

Coder	John Reap	Date	8/25/2008
Text Segment	Article	Type	Memo
Reference	Huppes, G. and M. Ishikawa (2005). A Framework for Quantified Eco-efficiency Analysis. *Journal of Industrial Ecology* 9(4): 25-41.		

"…eco-efficiency is an instrument...indicating an empirical relation in economic activities between environmental cost or value and environmental impact."

Eco-efficiency is the overarching concept in this paper. As the cited quote reveals, it mixes economic and environmental impact information; this combination often takes the form of a ratio. It has the properties of degree which varies from low to high and of economic scale which varies from micro to macro.

Unfortunately, the authors devote most of the paper to discussions about problems with calculating environmental and economic values. Problems with LCA such as the midpoint vs. endpoint debate are mentioned. They dwell on preferences and trade-off decisions.

Potential concepts: eco-efficiency (P: degree D: low to high; P: economic scale D: micro to macro)

Table 207: Summary of potential concepts, properties and dimensions for Huppes 2005

Concepts	Properties	Dimensions
Eco-efficiency	Degree	Low to high
	Economic scale	Micro to macro

Coder	John Reap	Date	7/15/2008
Text Segment	Paper	Type	Memo
Reference	Isalgue, A., H. Coch and R. Serra (2007) "Scaling laws and the modern city" *Physica A*, 382: 643-649.		

"…in relation to modern developed urban spaces…it is possible to find a reasonable continuity with the types of scales seen in living organisms..."

The authors focus on three concepts: urban spaces, energetic scaling and transport networks. Urban spaces have properties such as population, services, mass and energy consumption. The first two properties of urban spaces help classify and relate them to the energetic scaling concept. Numbers of people in an urban space and the availability of services such as education, healthcare clearly guided selection of urban spaces in this study. Population varies dimensionally by number of inhabitants while services vary by service and from incomplete to complete.

Energetic scaling and transport networks are assigned the same structure of properties and dimensions by the authors. Both possess the by mass property because both are examined from a mass scaling perspective. This property varies between abiotic and biotic, and in the case of transport networks it varies from suboptimal to optimal.

The authors argue that the energetic scaling and transport networks of urban spaces approach biotic configurations when scaled by mass. They further suggest that transport networks approach optimality as they approach biotic configurations.

Potential Concepts: urban spaces (P: population D: number of inhabitants; P: services D: by service, D: incomplete to complete; P: mass D: high to low; P: energy consumption D: high to low), energetic scaling (P: by mass D: abiotic to biotic), transport networks (P: by mass D: abiotic to biotic, D: suboptimal to optimal)

Table 208: Summary of potential concepts, properties and dimensions Isalgue 2007

Concepts	Properties	Dimensions
Urban space	Population	Number of inhabitants
	Services	By service
		Incomplete to complete
	Mass	High to low
	Energy consumption	High to low
Energetic scaling	By mass	Abiotic to biotic
Transport networks	By mass	Abiotic to biotic
		Suboptimal to optimal

Coder	John Reap	Date	7/27/2008
Text Segment	Abstract – Paragraph 11	Type	Memo
Reference	Jeswiet, J. and M. Hauschild (2005). "EcoDesign and future environmental impacts." *Materials and Design* 26: 629-634.		

"…LCA includes the entire life cycle of product, from cradle to grave..."

Life cycle is a dominant concept in the coded text. The authors give two distinct meanings to the concept. The first describes life cycle engineering as an umbrella idea that captures many others. The second meaning ties the life cycle concept to the analytical tool of life cycle assessment. This usage gives it the property of scope which varies from framework to assessment tool. Life cycles also have stages which vary from cradle to grave, as indicated by the cited passage.

Potential Concepts: life cycle (P: scope D: framework to assessment tool; P: stage D: cradle to grave)

Text Segment	Paragraph 5	Type	Memo

"…LCE is: Engineering activities…with the goal of protecting the environment and conserving resources, while encouraging economic progress,…sustainability…and minimizing pollution..."

While defining life cycle engineering, the author's introduce a number of concepts that often emerge from DfE publications. Sustainability is present with its traditional properties of economic and environmental sustainability. The resource reduction concept appears with emissions minimization.

Potential Concepts: life cycle (P: scope D: framework to assessment tool; P: stage D: cradle to grave), sustainability (P: economic D:?; P: environmental D: ?), resource reduction, emissions minimization

Text Segment	Paragraph 20-25	Type	Memo

"Getting the overall focus right in Product Design with an eye to Disassembly, Recycling and (re)Manufacturing..."

Here, the reuse concept takes center stage. The authors mention a number of strategies that one might employ to facilitate reuse of materials. These range from recycling to remanufacture.

Potential Concepts: life cycle (P: scope D: framework to assessment tool; P: stage D: cradle to grave), sustainability (P: economic D:?; P: environmental D: ?), resource reduction, emissions minimization, reuse (P: strategies D: recycling to remanufacture)

Table 209: Summary of potential concepts, properties and dimensions for Jeswiet 2007

Concepts	Properties	Dimensions
Life cycle	Scope	Framework to assessment tool
	Stage	Cradle to grave
Sustainability	Economic	?
	Environmental	?
Resource reduction	?	?
Emissions minimization	?	?
Reuse	Strategy	Recycling to remanufacture

Coder	John Reap	Date	10/2/2008
Text Segment	Abstract	Type	Memo
Reference	Jeswiet, J. and M. Hauschild (2008). "Market forces and the need to design for the environment." *Int. J. of Sustainable Manufacturing* 1(1-2): 41-57.		

The abstract contains a number of concepts, but from the perspective of concepts related to EBDM guidance, only <u>hazard avoidance</u> appears in the form of the <u>strategy</u> of <u>toxic material avoidance</u>.

Potential Concepts: hazard avoidance (P: strategy D: toxic material avoidance)

Text Segment	Paragraph 17-25	Type	Memo

"…keeping environmental impact to a minimum and keeping resource use and waste to a minimum..."

Environmental impact is an overarching theme in EBDM, but it is quite broad and does not help one see the changes needed to minimize it. Concepts such as <u>resource reduction</u>, <u>reuse</u> and <u>emissions minimization</u>, specified using properties such as <u>strategy</u>, more accurately encapsulate the guidance found in this paper. Resource reduction strategies include: <u>waste minimization</u>, <u>efficiency</u> and <u>product dematerialization</u>; for reuse, one sees strategies from <u>material recycling to product reuse</u>. Later in the section, resource reduction gains the property of <u>type</u> which one dimensions as either <u>energy or material</u>.

The <u>life cycle</u> concept appears in this section. Hazard avoidance reappears with a new strategy of <u>hazardous waste min</u>.

Potential Concepts: hazard avoidance (P: strategy D: toxic material avoidance, hazardous waste min.), resource reduction (P: strategy D: waste min., efficiency, product dematerialization; P: type D: energy or material), reuse (P: strategy D: material recycling to product reuse), emissions minimization, life cycle

Text Segment	Paragraph 26-end	Type	Memo

"…foregoing DfE axioms can be translated into concrete actions…as expressed in the following checklist..."

The author's "checklist" mentioned contains many sub-categories of the concepts and dimensions already mentioned. For example, recommendations to design for disassembly or to clearly label different materials fall under the previously mentioned material recycling to product reuse dimension for the reuse concept.

However, one new concept and a few new strategies are present. Renewable is one new idea that does not clearly fit within any of the previously mentioned concepts. It has the type property which takes the discrete dimensions of energy or material. Resource reduction adds the strategy of life extension while reuse gains repair. Hazard avoidance adds the substitution strategy.

Potential Concepts: hazard avoidance (P: strategy D: toxic material avoidance, hazardous waste min., substitution), resource reduction (P: strategy D: waste min., efficiency, product dematerialization, life extension; P: type D: energy or material), reuse (P: strategy D: material recycling to product reuse, repair), renewable (P: type D: energy or material), emissions minimization, life cycle

Table 210: Summary of potential concepts, properties and dimensions for Jeswiet 2008

Concepts	Properties	Dimensions
Life cycle	?	?
Hazard avoidance	Strategy	Toxic material avoidance, hazardous waste min., substitution
Resource reduction	Strategy	Waste min., efficiency, product dematerialization
	Type	Material or energy
Emissions minimization	?	?
Reuse	Strategy	Material recycling to product reuse, repair
Renewable	Type	Energy or material

Coder	John Reap	Date	11/30/2008
Text Segment	Abstract	Type	Memo
Reference	Jin, Y., D. Wang and F. Wei (2004). "The ecological perspective in chemical engineering." *Chemical Engineering Science* 59(8-9): 1885-1895.		

"Environmental sustainability is a stand to stay within forecasted limits in the resources and renewability capacity…"

The abstract contains many concepts that receive further development in the paper's body. The concept of <u>sustainability</u> is present, and the author attributes the <u>version</u> property to this concept. It varies discretely between <u>mainstream and environmental</u>. Statements about resource limits and renewable capacity point to the ecological concept of <u>carrying capacity</u>. The abstract also mentions material efficiency, energy efficiency, toxicity and recycling. These ideas point to concepts of <u>consumption reduction</u>, <u>hazard avoidance</u>, and <u>reuse</u>.

Potential Concepts: sustainability (P: version D: mainstream or environmental), carrying capacity, consumption reduction, hazard avoidance, reuse

Text Segment	Paragraphs 28-29	Type	Memo

"Both seek...efficiency and dematerialization so that the amount of polluting waste is decreased to within the Earth's cleansing capacity."

This statement and its surrounding paragraphs contain the concept of <u>emissions reduction</u> with the associated property of <u>strategy</u> which has the dimension of <u>efficiency</u>. <u>Substitution</u> is seen as a <u>strategy</u> for hazard avoidance. One also finds the properties of <u>cleansing capacity</u> and <u>renewability</u>. Knowing something about either of these helps one understand the environment's ability to absorb wastes and provide resources – its carrying capacity.

Potential Concepts: sustainability (P: version D: mainstream or environmental), carrying capacity (P: cleanings capacity D:?; P: renewability D: ?), consumption reduction, hazard avoidance (P: strategy D: substitution), reuse, emissions reduction (P: strategy D: efficiency)

Text Segment	Para. 31-36	Type	Memo

"…industrial ecology…is systems engineering based on cycling to minimize waste by using any waste stream as the source material of another process after the manner of nature cycles."

While the authors continue to think in terms of waste, their examples point to the concept of reuse. In fact, their examples describe different <u>strategies</u> of reuse ranging from <u>recycling to remanufacture</u>. The authors seem to believe that the structure of reuse systems is of some importance. They separate eco-industrial parks and integrated bio-systems from statements about recycling and remanufacturing. So, their discussion incorporates the property of <u>structure</u> which has dimensions of <u>linear to cyclic</u> and <u>separate to biologically integrated</u>.

Potential Concepts: sustainability (P: version D: mainstream or environmental), carrying capacity (P: cleanings capacity D:?; P: renewability D: ?), consumption reduction, hazard avoidance (P: strategy D: substitution), reuse (P: structure D: linear to cyclic, separate to biologically integrated), emissions reduction (P: strategy D: efficiency)

Text Segment	Para. 40-44	Type	Memo

"…self-evident principles for good ecological practice..."

Five "principles" form the conclusion of this paper. The first three can be represented using one or more of the previously identified concepts of consumption reduction and emissions reduction. The fifth seems merely to emphasize the importance of technical development.

1. Element utilization – a call for efficient resource use to reduce consumption
2. End-use consideration – a call to limit emissions
3. Simultaneous production – authors' description emphasizes resource efficiency and elimination of wastes
4. Flexible transformation
5. Process evolution – technological development

However, the fourth appears to be a call for process robustness. It is not wholly contained in prior concepts because the authors' description centers on the ability to follow multiple process routes to the same end product, not higher efficiency and fewer wastes. This suggests the existence of a separate concept, <u>process flexibility</u>.

Potential Concepts: sustainability (P: version D: mainstream or environmental), carrying capacity (P: cleanings capacity D:?; P: renewability D: ?), consumption reduction, hazard avoidance (P: strategy D: substitution), reuse (P: structure D: linear to cyclic, separate to biologically integrated), emissions reduction (P: strategy D: efficiency), process flexibility

Table 211: Summary of potential concepts, properties and dimensions for Jin 2004

Concepts	Properties	Dimensions
Sustainability	Versions	Mainstream or environmental
Carrying capacity	Cleansing capacity	?
	Renewability	?
Consumption reduction	Strategy	Recycling
Hazard avoidance	Strategy	Substitution
Reuse	Structure	Linear to cyclic
		Separate to biologically integrated
Emissions reduction	Strategy	Efficiency
Process flexibility	?	?

Coder	John Reap	Date	7/23/2008
Text Segment	Abstract – para. 3	Type	Memo
Reference	Jofre, S., K. Tsunemi and T. Morioka (2003). "A new eco-design strategy to assess sustainable environmental innovations". Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, IEEE.		

"…paper analyzes and discusses the potential role of evolutionary theories in environmental innovation..."

Environmental innovation is the central concept in this DfE article. It encompasses the ways in which products and, more generally, systems are transformed to better fit environmental constraints. Properties such as emphasis, varying from product to system, and strategy, varying from evolutionary to revolutionary, are apparent.

Potential Concepts: Environmental innovation (P: emphasis D: product to system; P: strategy D: evolutionary to revolutionary)

Text Segment	Para.: 5-6	Type	Memo

"…innovations should be conducted as early as possible during the design process..."

Design process is an obvious concept that occurs in first few pages of the article. The primary property mentioned by the authors is phase. The dimensions of a design phase are requirements definition to detail design. The authors contend that decisions early in the design phase generate the majority of a product's environmental impacts, and therefore, they strongly influence environmental innovation.

Potential Concepts: Environmental innovation (P: emphasis D: product to system; P: strategy D: evolutionary to revolutionary), design process (P: phase, D: requirements definition to detail design)

Text Segment	Para.: 9-13	Type	Memo

"…philosophy behind factors 4 and 10 is the dematerialization of production and consumption in which all needed products and services...are to be met with less resources."

Dematerialization appears as an important concept in the article, but the term is something of a misnomer. The authors group reductions in energy consumption under it; so, a better name for concept is <u>resource reduction</u>. Associated properties include <u>efficiency</u> and <u>function provision</u>. Efficiency varies from <u>high to low</u>, and function provision's dimensions are <u>product or service</u>. The authors state that resource reduction through high efficiency is necessary. They also suggest that function provision by services advances this cause. However, they believe that achieving the vaguely defined concept of <u>sustainability</u> is not simply a matter of reducing resource consumption.

Potential Concepts: Environmental innovation (P: emphasis D: product to system; P: strategy D: evolutionary to revolutionary), design process (P: phase, D: requirements definition to detail design), resource reduction (P: efficiency D: high to low; P: function provision D: product or service), sustainability

Text Segment	Para.: 19	Type	Memo

Though it receives little explicit attention, the concept of <u>life cycle assessment</u> appears in a number of places in this article. It is mentioned explicitly in paragraph 19, and it seems to be the only clearly environmental tool used in the author's environmental design method.

Potential Concepts: Environmental innovation (P: emphasis D: product to system; P: strategy D: evolutionary to revolutionary), design process (P: phase, D: requirements definition to detail design), resource reduction (P: efficiency D: high to low; P: function provision D: product or service), sustainability, life cycle assessment

Table 212: Summary of potential concepts, properties and dimensions for Jofre 2003

Concepts	Properties	Dimensions
Environmental innovation	Emphasis	Product to system
	Strategy	Evolutionary to revolutionary
Design process	Phase	Requirements definition to detail design
Resource reduction	Efficiency	High to low
	Function provision	Product or service
Sustainability	?	?
Life cycle assessment	?	?

Coder	John Reap	Date	7/23/2008
Text Segment	Para.: 1-4; 14-16	Type	Memo
Reference	Knight, W. and M. Curtis (2002). Measuring your ecodesign. <u>Manufacturing Engineer</u>: 64-69.		

"Early design decisions on materials and processes determine the ease of disassembly and the overall environmental impact of a product."

<u>Design process</u> is a concept that appears early in this article. Its main property is <u>stage</u> which varies from <u>requirements to detail design</u>. However, the main concept in the work is <u>disassembly</u>. It has properties such as <u>cost</u>, <u>time</u> and <u>avoided environmental impact</u> which vary from <u>low to high</u>. It also has properties such as <u>process</u> and <u>sequence</u> which lack apparent dimensions.

Later in the article, a dimension for disassembly's sequence property appears. They can vary from <u>suboptimal to optimal</u>.

Potential Concepts: Design process (P: stage D: requirements to detail design), Disassembly (P: cost D: low to high; P: time D: low to high; P: avoided environmental impact D: low to high; P: process D: ?; P: sequence D: suboptimal to optimal)

Text Segment	Para.: 5-9; 12	Type	Memo

"…MET points indicator takes into account...material cycles, energy use and toxic emissions…"

<u>Life cycle assessment</u> is an important, though poorly explained, concept in this work. At its core, though, this article's use of MET points to account for material, energy and toxic emissions boils down to the concepts of <u>resource minimization,</u> <u>reuse</u> and <u>substance hazard mitigation</u>. When energy use is mentioned, it appears in the context of

resource avoidance and efficiency. Reuse's property is type which varies from recycling to remanufacture.

Potential Concepts: Design process (P: stage D: requirements to detail design), Disassembly (P: cost D: low to high; P: time D: low to high; P: avoided environmental impact D: low to high; P: process D: ?; P: sequence D: ?), life cycle assessment, resource minimization (P: avoidance D: ?; P: efficiency D: ?), reuse (P: type D: recycling to remanufacture)

Table 213: Summary of potential concepts, properties and dimensions for Knight 2002

Concepts	Properties	Dimensions
Disassembly	Cost	Low to high
	Time	
	Avoided environmental impact	
	Sequence	Suboptimal to optimal
	Process	?
Design process	Stage	Requirements to detail design
Resource minimization	Avoidance	?
	Efficiency	?
Reuse	Type	Recycling to remanufacture
Substance hazard mitigation	?	?

Coder	John Reap	Date	11/9/2008
Text Segment	Abstract – para. 7	Type	Memo
Reference	Korhonen, Jouni (2007). "Special Issue: of the Journal of Cleaner Production, 'From Material Flow Analysis to Material Flow Management': strategic sustainability management on a principle level" *Journal of Cleaner Production* 15: 1585-1595.		

"…sustainable development [has] three dimensions, economic, social and ecological..."

Sustainability and different frameworks meant to achieve it dominate the opening two pages of this paper. As the quote indicates, one learns that sustainability possesses the property of elements which one dimensions as social, economic and environmental. One also sees that the author intends to compare The Natural Step principles with those associated with eco-efficiency.

Natural Step is largely concerned with three concepts found in other EBDM literature: emissions, resource consumption and ecosystems. The first two concepts share the properties of rate and source. Rate varies from low to high while source varies discretely between lithosphere and society. Ecosystems possess the property of integrity which varies from collapsed to healthy.

Potential Concepts: sustainability (P: element D: social, economic and environmental), eco-efficiency, emissions (P: rate D: low to high; P: source D: lithosphere or society), resource consumption (P: rate D: low to high; P: source D: lithosphere or society), ecosystems (P: integrity D: collapsed to healthy)

Text Segment	Page 1593 - end	Type	Memo

"Low diversity reduces the capacity of the system to adapt to changing external and internal conditions."

Economic diversity enters the author's list of concepts late in the paper. However, he is one of few, if not the only, authors to discuss this topic in the context of sustainability. He seems to attach two properties to his concept. First, he talks about market efficiency which varies from low to high. Then, in the same sentence, he mentions sector number which also varies from low to high. He asserts that high economic diversity as measured by sector number confers resilience to economic systems. Interestingly, he believes that the cost of this diversity is low market efficiency for a number of economic sectors.

Potential Concepts: sustainability (P: element D: social, economic and environmental), eco-efficiency, emissions (P: rate D: low to high; P: source D: lithosphere or society), resource consumption (P: rate D: low to high; P: source D: lithosphere or society), ecosystems (P: integrity D: collapsed to healthy), economic diversity (P: market efficiency D: low to high; P: sector number D: low to high)

Table 214: Summary of potential concepts, properties and dimensions for Korhonen 2007 #1

Concepts	Properties	Dimensions
Sustainability	Element	Social, economic and environmental
Emissions	Rate	Low to high
	Source	Lithosphere or society
Resource consumption	Rate	Low to high
	Source	Lithosphere or society
Ecosystems	Integrity	Collapsed to healthy
Economic diversity	Market efficiency	Low to high
	Sector number	Low to high

Coder	John Reap	Date	11/30/2008
Text Segment	Article	Type	Memo
Reference	Korhonen, J. (2007). "Environmental planning vs. systems analysis: Four prescriptive principles vs. four descriptive indicators." *Journal of Environmental Management* 82(1): 51-59.		

Concepts such as sustainability and the life cycle are present in this article. For instance, one sees that the life cycle concept has the property of phases which vary from cradle to grave. However, four "prescriptive principles for environmental planning" form the core of the paper and provide its important concepts. These principles are:

1. Roundput
2. Cooperation
3. Diversity
4. Locality

Roundput is largely equivalent to reuse. It includes strategies such as recycling and cascades. The author notes that one can reuse energy by cascading it through multiple system elements. In so doing, he introduces the property of type to reuse which varies between energy or material. The principle also contains the concept of renewable resources.

Though presented as a separate principle, cooperation in a physical sense is subsumed by roundput. Mentioned types of cooperation include material exchanges and cascades. Both of these forms of cooperation are considered part of roundput.

Diversity is a concept with the properties of type and magnitude. Type varies discretely by sector, company size and public vs. private. Using these measures, the magnitude of a system's diversity could vary from low to high. The boundary for said system is not apparent in the definition of cooperation. One might simply draw it around all actors having a cooperative relationship, or one might resort to the final principle.

Locality is a concept with little in the way of definition besides proximity of actors.

Potential Concepts: sustainability, life cycle (P: phases D: cradle to grave), reuse (P: strategies D: recycling, cascades; P: type D: energy or material), renewable resources, diversity (P: type D: sector, company size and public vs. private; P: magnitude D: low to high), locality

Table 215: Summary of potential concepts, properties and dimensions for Korhonen 2007 #2

Concepts	Properties	Dimensions
Sustainability	Element	Social, economic and environmental
Life cycle	Phases	Cradle to grave
Reuse	Strategies	Recycling
		Cascades
	Type	Energy or material
Renewable resources	?	?
Diversity	Type	Sector
		Company size
		Public vs. private
	Magnitude	Low to high

Coder	John Reap	Date	12/20/2008
Text Segment	Abstract – para. 6	Type	Memo
Reference	Krotscheck, C. and M. Narodoslawsky (1996). "The Sustainable Process Index a new dimension in ecological evaluation." *Ecological Engineering* 6(4): 241-258.		

"…area becomes the limiting factor of a sustainable economy. …area needed to provide the raw materials and energy…and to accommodate by-product flows…"

Three concepts appear in the abstract: <u>sustainability</u>, <u>resource consumption</u> and <u>emissions</u>. The latter two are developed to a greater extent as made evident by the quotation. The authors equate greater area requirements with larger consumptive and waste flows. So, both resource consumption and emissions have the property of <u>level</u> which is dimensioned by <u>area</u>. Resource consumption is also further defined by the <u>type</u> of resource consumed; the dimensions are <u>material or energy</u>.

Potential Concepts: sustainability, resource consumption (P: level D: area; P: type D: material or energy), emissions (P: level D: area)

Text Segment	Para. 7 - 10	Type	Memo

"…material flows must not exceed the local assimilation capacity and should be smaller than natural fluctuations…"

The author introduces two requirements for sustainability connected with the emissions concept. He notes that emissions must not exceed "local assimilation" or "natural fluctuations." Both ideas give more precise definition to the previously identified level property. One could say that level varies dimensionally from <u>below to above assimilation</u> and by <u>percentage of fluctuation</u>.

Potential Concepts: sustainability, resource consumption (P: level D: area; P: type D: material or energy), emissions (P: level D: area, below to above assimilation, percent of natural fluctuation)

Text Segment	Para. 11-12	Type	Memo

"Renewable resources…extracted at a rate…not exceed the local fertility…natural variety…must be sustained…"

In these paragraphs, the authors convey two final sustainability principles and provide two associated concepts. First, they emphasize the importance of <u>renewable resources</u>, and then, they highlight <u>diversit</u>y. The focus on the properties of <u>rate</u> for renewable resources and <u>number of species</u> for diversity, providing dimensions of <u>below to beyond replacement</u> and <u>low to high</u> for each.

The remainder of the article quantifies these concepts in terms of algebraic area formulas and presents a simple example.

Potential Concepts: sustainability, resource consumption (P: level D: area; P: type D: material or energy), emissions (P: level D: area, below to above assimilation, percent of natural fluctuation), renewable resources (P: rate D: below to beyond replacement), biodiversity (P: number of species D: low to high)

Table 216: Summary of potential concepts, properties and dimensions for Krotscheck 1996

Concepts	Properties	Dimensions
Sustainability	?	?
Resource consumption	Level	Area
	Type	Material or energy
Emissions	Level	Area
		Below to above assimilation
		Percent of natural fluctuation
Renewable resources	Rate	Below to beyond replacement
Biodiversity	Number of species	Low to high

Coder	John Reap	Date	7/15/2008
Text Segment	Article	Type	Memo
Reference	Lee, B.H. and K. Ishii (1997) "Demanufacturing Complexity Metrics in Design for Recyclability" *IEEE: 0-7803-3808-1*.		

"…paper proposes a new design chart and associated recycling complexity metrics to aid with recyclability..."

Reuse is the central idea in this DfE article. It's property of type varies from recycling to remanufacturing.

Potential Concepts: Reuse (P: type D: recycling to remanufacturing)

Table 217: Summary of potential concepts, properties and dimensions for Lee 1997

Concepts	Properties	Dimensions
Reuse	Type	Recycling to component remanufacture

Coder	John Reap	Date	12/??/2008
Text Segment	Abstract	Type	Memo
Reference	Lindholm, M. E. (2003). Toward Environmentally Conscious Product Design - a Comprehensive DfE Implementation in New Generation Cellular Phones. Electronics and the Environment, 2003. IEEE International Symposium on Salo, Finland, IEEE.		

"…aim is to create products with less environmental impact…using the starting points of material recyclability, reduction of elimination of harmful substances…"

Here, we see that Nokia counsels a focus on the commonly observed EBDM concepts of reuse and hazard reduction. The preferred reuse strategy appears to be material recycling, and the strategies for reducing hazards are material reduction and substitution.

Potential Concepts: reuse (P: strategy D: material recycling), hazard reduction (P: strategy D: toxic material reduction, toxic material substitution)

Text Segment	Para. 1-4	Type	Memo

"…environmental responsibility of a manufacturer…will extend from supplier operations through production, use and ultimately, recycling and / or disposal."

In this initial section, the authors mention the importance of the life cycle concept. Its property of stages appears next to the common dimension of cradle to grave.

Potential Concepts: reuse (P: strategy D: material recycling), hazard reduction (P: strategy D: toxic material reduction, toxic material substitution), life cycle (P: stage D: cradle to grave)

Text Segment	Para. 5-12	Type	Memo

"…minimize the consumption of energy and materials while maximizing the possibilities for their reuse and recycling."

As the article progresses, one sees the importance of resource consumption enter into the authors thinking about EBDM. This citation clearly reveals their concern.

Their bulleted list of recycling criteria reiterates the importance of previously introduced concepts while mentioning renewable resources.

Potential Concepts: reuse (P: strategy D: material recycling), hazard reduction (P: strategy D: toxic material reduction, toxic material substitution), life cycle (P: stage D: cradle to grave), resource consumption, renewable resources

Table 218: Summary of potential concepts, properties and dimensions for Lindholm 2003

Concepts	Properties	Dimensions
Reuse	Strategy	Material recycling
Hazard reduction	Strategy	Toxic material reduction
		Toxic material substitution
Life cycle	Stage	Cradle to grave
Resource consumption	?	?
Renewable resources	?	?

Coder	John Reap	Date	10/20/2008
Text Segment	Article	Type	Memo
Reference	Linton, J.D. (2002). DEA: A Method for Ranking the Greeness of Design Decisions. *Journal of Mechanical Design* 124: 145-150.		

"…impacts are input variables and the unit price of the polymer is the output variable."

Linton's article is noteworthy for two major reasons. First, it focuses on the concept of economic efficiency. This efficiency is a function of standard cost and the cost of pollution; it has the ratio property which varies from low to high. A high ratio is preferable because it accurately represents the costs of the pollutant "inputs" associated with the decision.

The second reason for noting this article is the author's reiteration of the common EBDM concepts of resource consumption, emissions and hazards. His pollution indices contain them. The choice of indices reveals the resource consumption property of type which varies between material or energy.

Table 219: Summary of potential concepts, properties and dimensions for Linton 2002

Concepts	Properties	Dimensions
Economic efficiency	Ratio	Low to high
Resource consumption	Type	Material or energy
Emissions	?	?
Hazards	?	?

Coder	John Reap	Date	11/12/2008
Text Segment	Abstract – para. 3	Type	Memo
Reference	Manley, J. B., P. T. Anastas and B. W. Cue Jr (2008). "Frontiers in Green Chemistry: meeting the grand challenges for sustainability in R&D and manufacturing." *Journal of Cleaner Production* 16(6): 743-750.		

"Green Chemistry...reduce or eliminate the use and generation of substances hazardous to human health and the environment."

The opening paragraphs mention three concepts often found during coding this type of literature. First, the very definition of Green Chemistry focuses on the concept of <u>hazard reduction</u>. Specifically, it focuses on hazards caused by toxic materials found in products or used during production. Hazard reduction <u>strategies</u> are also present in the form of <u>reduction</u> and <u>elimination</u>. The opening paragraphs also mention the concepts of the <u>life cycle</u> and <u>sustainability</u>. Statements about Green Chemistry's concern with molecular sustainability reveal that the latter concept has the property of <u>scale</u> which varies from <u>molecular to macroscopic</u>.

Potential Concepts: hazard reduction (P: strategies D: reduction, elimination), life cycle, sustainability (P: scale D: molecular to macroscopic)

Text Segment	Para. 4-13	Type	Memo

"From origins of feedstocks…through all manufacturing, and product design to the consequences following the end of commercial life..."

This set of paragraphs largely serves to further define two of the three concepts found in the first few. One sees that the authors begin to think about the implications of Green Chemistry over the entire life cycle. Life cycle gains the property of <u>phases</u> which varies from <u>feedstock origination to end-of-life</u>. Sustainability is pictured with three <u>elements</u>, <u>economic</u>, <u>social</u> and <u>environmental</u>.

Potential Concepts: hazard reduction (P: strategies D: reduction, elimination), life cycle (P: phases D: feedstock origination to end-of-life), sustainability (P: scale D: molecular to macroscopic; P: elements D: economic, social, environmental)

Text Segment	Para. 14-end	Type	Memo

"…degrades rapidly when released to the environment..."

Another concept emerges in the final set of paragraphs. Statements about the importance of biodegradation and short life spans in the environment coupled with concerns about endocrine disruption reveal the presence of the <u>biocompatibility</u> concept.

The discussion about "E" factors brings another concept to light. The authors are generally concerned about <u>resource consumption</u>, and they promote the <u>strategy</u> of <u>efficiency</u> to reduce it.

Potential Concepts: hazard reduction (P: strategies D: reduction, elimination), life cycle (P: phases D: feedstock origination to end-of-life), sustainability (P: scale D: molecular to macroscopic; P: elements D: economic, social, environmental), biocompatibility, resource consumption (P: strategy D: efficiency)

Table 220: Summary of potential concepts, properties and dimensions for Manley 2008

Concepts	Properties	Dimensions
Hazard reduction	Strategy	Reduction
		Elimination
Life cycle	Phases	Feedstock origination to end-of-life
Sustainability	Scale	Molecular to macroscopic
	Elements	Economic
		Social
		Environmental
Biocompatibility	?	?
Resource consumption	Strategy	Efficiency

Coder	John Reap	Date	7/22/2008
Text Segment	Article	Type	Memo
Reference	Matthews, H. Scott and Gregory C. Chambers (1997) "Unraveling the Environmental Product Design Paradox" *Proceedings of the IEEE International Symposium on Electronics and the Environment* San Francisco, CA, USA.		

"As global mandates on end-of-life product disposition finally go in to effect..."

The concept of end-of-life disposition provides the context for this article. It has the property of type which varies from landfill to product reuse. Within this context, the authors focus on the end of the dimensional range of EOL disposition dealing with reuse. Reuse can be considered a concept unto itself. The types of reuse vary from recycling to product reuse. Another interesting property that emerges from the article is path. Material can follow one route back to manufacturer, or it can diffuse into the market, its end-of-life value consumed by opportunistic recyclers and others. The path property seems to vary from single channel to multi-channel, and another dimension appears to be manufacturer controlled to third party controlled.

Potential Concepts: end-of-life disposition (P: type D: landfill to product reuse), reuse (P: type D: recycling to product reuse; P: path D: single to multi-channel, D: manufacturer controlled to third party controlled)

Table 221: Summary of potential concepts, properties and dimensions for Matthews 1997

Concepts	Properties	Dimensions
end-of-life disposition	Type	Landfill to product reuse
Reuse	Type	Recycling to product reuse
	Path	Single to multi-channel
		Manufacturer controlled to third party controlled

Coder	John Reap	Date	7/15/2008
Text Segment	Article	Type	Memo
Reference	Matzke, Jill S., C. Chew and T-S. Wu (1998) "A Simple Tool to Facilitate Design for the Environment at Apply Computer". *Proceedings of the 1998 IEEE International Symposium on Electronics and the Environment, ISEE,* May 4-6, Oak Brook, IL, USA.		

In this early article from industry, the authors describe a simple tool for informing different business processes of applicable design for environment standards. Little detail about the specific standards or resultant guidelines is available. However, some of their sample outputs contain references to materials and energy. This suggests that energy and material consumption are important. The reference to materials might also occur because the electronics industry uses many materials of concern. Resource consumption and hazards reduction, then, appear to be the concepts present in this article.

Potential Concepts: resource consumption, hazards reduction

Table 222: Summary of potential concepts, properties and dimensions for Matzke 1998

Concepts	Properties	Dimensions
Hazards reduction	?	?
Resource consumption	?	?

Coder	John Reap	Date	10/3/2008
Text Segment	Abstract	Type	Memo
Reference	McAloone, T.C. (2007). "A Competence-Based Approach to Sustainable Innovation Teaching: Experiences Within a New Engineering Program." *Journal of Mechanical Design* 129: 769-778.		

"Innovation and sustainability are two areas upon which Scandinavian countries place a great deal of attention"

The abstract primarily communicates the importance of <u>sustainability</u> in the author's redeveloped mechanical engineering design curriculum. However, I do not get a sense of sustainability's meaning for the author.

Potential Concepts: sustainability

Text Segment	Section 5	Type	Memo

"…shift in focus from the exchange and consumption of goods to the exchange of competences and the consumption of services has been emerging."

Skipping to the section reserved for discussion of the new curriculum's sustainable engineering content, one finds two concepts: sustainability and <u>life cycle</u>. <u>Consumption</u> is introduced as a property of sustainability that varies from <u>product to service</u>. Citing other work, the authors state that a shift toward service consumption leads to a less unsustainable society. The life cycle clearly has the property of <u>phase</u> which includes dimensions from <u>material extraction to end of life</u>.

Potential Concepts: sustainability (P: consumption D: product to service), life cycle (P: phase D: material extraction to end of life)

Table 223: Summary of potential concepts, properties and dimensions for McAloone 2007

Concepts	Properties	Dimensions
Life cycle	Phase	Material extraction to end of life
Sustainability	Consumption	Product to service

Coder	John Reap	Date	11/15/2008
Text Segment	Article	Type	Memo
Reference	McAuley, J. W. (2003). "Global Sustainability and Key Needs in Future Automotive Design." *Environ. Sci. Technol.* 37(23): 5414-5416.		

In his discussion of needs for sustainable automobiles, the author focuses on three major concepts: <u>resource consumption</u>, <u>emission reduction</u> and <u>reuse</u>. As one might expect from a paper about vehicles, energy is the resource of primary importance which leads to the obvious property of <u>type</u> for resource consumption. The dimension for this property is <u>energy</u> in this article. Another property for resource consumption is <u>strategy</u>, and the author repeatedly mentions <u>efficiency</u> as the car industry's best approach to cutting resource consumption.

His discussion about reuse hints at <u>strategies</u> such as <u>remanufacture</u> and <u>recycling</u>. He sites efforts to improve design for disassembly, which suggests that he believes some components are worth extracting prior to shredding.

Potential Concepts: resource consumption (P: type D: energy; P: strategy D: efficiency), reuse (P: strategies D: remanufacture, recycling)

Table 224: Summary of potential concepts, properties and dimensions for McAuley 2003

Concepts	Properties	Dimensions
Reuse	Strategy	Remanufacture
		Recycling
Resource Consumption	Type	Energy
	Strategy	Efficiency

Coder	John Reap	Date	11/15/2008
Text Segment	Article	Type	Memo
Reference	Mihelcic, J. R., J. B. Zimmerman and A. Ramaswami (2007). "Integrating Developed and Developing World Knowledge into Global Discussions and Strategies for Sustainability. 1. Science and Technology." *Environ. Sci. Technol.* 41(10): 3415-3421.		

"…DfE process generated a number of design changes…increasing recycled content…eliminating all PVC...designing the chair for rapid disassembly…and using materials with a green chemistry composition..."

The authors list a series of technologies developed in developing countries ranging from rainwater collectors to anaerobic digesters. All of these technologies aim at reducing <u>resource</u> <u>consumption</u> and <u>reusing</u> waste energy and materials.

Potential Concepts: resource consumption, reuse

Table 225: Summary of potential concepts, properties and dimensions for Mihelcic 2007

Concepts	Properties	Dimensions
Reuse	?	?
Consumption	?	?

Coder	John Reap	Date	10/11/2008
Text Segment	Summary	Type	Memo
Reference	Murphy, C.F. (2001). Electronics. WTEC Panel Report on Environmentally Benign Manufacturing. Baltimore, International Technology Research Institute: 79-88.		

"…electronics manufacturing...result in high amounts of waste and wastewater, high usage of energy, and the emission of materials of concern…"

Environmental concerns and consequent design and manufacturing guidance focus on three concepts: emission reduction, resource reduction and hazard avoidance. Each of these is evident in the above quotation, and one learns about the different forms each takes as the section continues.

Potential Concepts: emission reduction, resource reduction, hazard avoidance

Text Segment	Page 79, Para. 1-2	Type	Memo

"…electronic product and component manufacturers have been proactive in the areas of life-cycle assessment (LCA)…"

Proceeding into the section, one encounters a few fleeting statements about the life cycle concept. However, the author's interest in the life cycle is not passing; the entire section is organized by the life cycle of electronic products from wafer manufacture to product disposal. Resource reduction acquires the strategy property which has the dimension of efficiency.

Potential Concepts: emission reduction, resource reduction (P: strategy D: efficiency), hazard avoidance, life cycle

Text Segment	Page 79-80 Para. 3-6	Type	Memo

"Focus areas within the electronics industry have been (1) materials of concern, including elimination and substitutions, (2) reduction in resource consumption…design for disassembly and reuse…emissions reduction…"

In the next few paragraphs, the author reiterates concepts found in the summary. He adds the concept of reuse to the mix, and a few properties and dimensions surface. One encounters the strategies of elimination and substitution for the hazard reduction concept. The property of type, dimensioned by material or energy, for resource reduction becomes discernable in the text.

Potential Concepts: emission reduction, resource reduction (P: type D: material or energy; P: strategy D: efficiency), hazard avoidance (P: strategy D: elimination, substitution), life cycle, reuse

Text Segment	Page 80-end, Para. 7-end	Type	Memo

The remainder of the section restates the themes mentioned in the first few pages in forms specific to the electronics industry. Only the reuse strategy of recycling is added during the other eight pages.

Potential Concepts: emission reduction, resource reduction (P: type D: material or energy; P: strategy D: efficiency), hazard avoidance (P: strategy D: elimination, substitution), life cycle, reuse (P: strategy D: material recycling)

Table 226: Summary of potential concepts, properties and dimensions for Murphy 2001

Concepts	Properties	Dimensions
Emission reduction	?	?
Resource reduction	Strategy	Efficiency
	Type	Material or energy
Hazard avoidance	Strategy	Elimination, substitution
Life cycle	?	?
Reuse	Strategy	Material recycling

Coder	John Reap	Date	7/26/2008
Text Segment	Article	Type	Memo
Reference	Nagel, M. H. and A. L. N. Stevels (2003). "Design for environment in the electronics industry, possibilities and limitations: a discussion and evaluation of product metrics." Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, IEEE.		

The life cycle concept appears early in the article, but it primarily establishes a context for the author's main thrust. One primarily learns that it has the property of stages which has the dimensions of cradle to grave. Each stage contributes to environmental impact.

Nagel and Stevels present a DfE metric that incorporates material, energy and toxicity. With regard to material, their approach emphasizes reduction and recycling. Taken together, the ideas presented in this article correspond to the concepts of resource reduction, reuse and hazardous substance minimization. Resource reduction has properties of strategy and type. Strategies include efficiency improvements and material avoidance in products. The type of resource reduced is either energy or material. Reuse and hazard reduction have the property of strategy which seems to have the rather narrow dimensions of recycling and reduction, respectively.

Table 227: Summary of potential concepts, properties and dimensions for Nagel 2003

Concepts	Properties	Dimensions
Life cycle	Stages	Cradle to grave
Resource reduction	Strategy	Efficiency, avoidance
	Type	Energy or material
Reuse	Strategy	Recycling
Hazardous material reduction	Strategy	Reduction

Coder	John Reap	Date	12/20/2008
Text Segment	Article	Type	Memo
Reference	Nguyen, H. X., T. Honda and R. Yamamoto (2003). Classification of ecomaterials in the perspectives of sustainability. Environmentally Conscious Design and Inverse Manufacturing, 2003. EcoDesign '03. 2003 3rd International Symposium on Tokyo, Japan, IEEE.		

The paper explains the importance of materials and materials engineering to environmentally benign development. In so doing, the authors mention major concepts such as resource reduction, reuse, hazard reduction and bio-compatibility. Properties for resource reduction include type and strategy which have the respective dimensions of energy or material and efficiency and durability. The other three concepts exhibit examples of different methods that one might call strategies. For reuse, the dimension for the strategy property is recycling, and for hazards and bio-compatibility, the dimensions are material substitution and biodegradability, respectively.

Table 228: Summary of potential concepts, properties and dimensions for Nguyen 2003

Concepts	Properties	Dimensions
Resource reduction	Type	Energy or material
	Strategy	Efficiency
		Durability
Reuse	Strategy	Recycling
Hazard reduction	Strategy	Material substitution
Bio-compatibility	Strategy	Biodegradability

Coder	John Reap	Date	12/1/2008
Text Segment	Article	Type	Memo
Reference	Noble, B. F. (2002). "The Canadian experience with SEA and sustainability." *Environmental Impact Assessment Review* 22(1): 3-16.		

A policy framework paper, Noble's work contains little in the way of principles and other forms of concrete guidance for environmental sustainability. The sustainability concept is present, and later in the paper, he mentions emissions and resource consumption. One could identify many concepts related to the social sciences and policy, but little else is present.

Potential Concepts: sustainability, emissions, resource consumption

Table 229: Summary of potential concepts, properties and dimensions for Noble 2002

Concepts	Properties	Dimensions
Sustainability	?	?
Emissions	?	?
Resource consumption	?	?

Coder	John Reap	Date	7/29/2008
Text Segment	Abstract	Type	Memo
Reference	Ny, H., J.P. MacDonald, G. Broman, R. Yamamoto, and K-H. Robert (2006). "Sustainability Constraints as System Boundaries: An Approach to Making Life-Cycle Management Strategic" *Journal of Industrial Ecology* 10(1-2): 61-77.		

Two overarching concepts dominate the abstract: sustainable management and life cycle. The abstract contrasts methods for assessing life cycles with a more abstract framework meant to allow sustainable management. It proposes melding the two. These two concepts and their related themes dominate the remainder of the article.

Potential Concepts: sustainable management, life cycle

Text Segment	Page 62-63	Type	Memo

"…many 'safe' materials have been commercialized, followed by later realization of negative effects on humans and the environment."

As the quote indicates, hazard minimization appears early in this paper, but significant detail is not added to the concept in these sections. The life cycle concept gains the property of extent which varies dimensionally from resource extraction to disposal.

Potential Concepts: hazard minimization, life cycle (P: extent D: resource extraction to disposal)

Text Segment	Page 64-66	Type	Memo

"…nature is not subject to systematically increasing concentrations of substances…from Earth's crust [and]…society..."

The material hazard concept is prevalent in this section, and one can distinguish the source property which has dimensions of nature or industry. The idea of natural degradation rests alongside statements about hazardous materials. The now familiar strategy property is present with the substitution dimension.

"…Dematerialization measures should here be taken in their widest possible meaning...leaner production…recycling…leasing…"

Dematerialization, another term for the resource reduction concept, is mentioned later in the text. Strategies including waste minimization, recycling and leasing give us a better understanding of this concept.

The authors counsel replacement of scarce materials with abundant ones. Abundance seems related to dematerialization, but it is also distinct. For now, I will maintain it as a concept.

Potential Concepts: natural degradation, hazard minimization (P: source D: nature or industry), dematerialization (P: strategy D: waste minimization, recycling and leasing), abundance

Table 230: Summary of potential concepts, properties and dimensions for Ny 2006

Concepts	Properties	Dimensions
Sustainable management	?	?
Life cycle	Extent	Resource extraction to disposal
Hazard minimization	Source	Nature or industry
Natural degredation	?	?
Dematerialization	Strategy	Waste minimization, recycling and leasing
Abundance	?	?

Coder	John Reap	Date	7/26/2008
Text Segment	Para.: 3-5	Type	Memo
Reference	O'Neill, M. (2003). "WEEE & RoHS and Trends in the Environmental Legislation in European Union." Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, IEEE.		

"…EU Directive on WEEE...places an obligation on the producers of electronics to take-back 'end-of-life' or waste products free of charge in an effort to reduce the amount of such waste going to landfill."

Emissions are one of the concepts motivating the European Union policies discussed by the author. Volume and toxicity are two properties of emissions gleaned from that text that both vary dimensionally from low to high. The policies are clearly meant to minimize the volume and toxicity of emissions.

Potential Concepts: emissions (P: volume D: low to high; P: toxicity D: low to high)

Text Segment	Para.: 3-5	Type	Memo

"Producers are obliged to finance the costs of recovery from municipal collection points, reuse, and recycling..."

Reuse also factors prominently into EU policies mentioned in the middle of the article. Strategies for reuse ranging from recycling to product reuse appear in these paragraphs.

Text Segment	Para.: 7-11	Type	Memo

"…requires…all products to remove and find feasible and safe alternatives to the substances."

After presenting policies dealing with reuse and emissions, emphasis shifts to the concept of hazardous substance minimization. Strategies for minimizing substance hazards range from avoidance to substitution in this article.

Table 231: Summary of potential concepts, properties and dimensions for O'Neill 2003

Concepts	Properties	Dimensions
Reuse	Strategy	Recycling to product reuse
Emissions	Volume	Low to high
	Toxicity	Low to high
Hazardous substance minimization	Strategies	Avoidance to substitution

Coder	John Reap	Date	7/23/2008
Text Segment	Article	Type	Memo
Reference	Pascual, O., C. Boks and A. Stevels (2003). Electronics ecodesign research empirically studied. Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, IEEE.		

The authors conducted an extensive DfE literature survey. They reported that the electronics community seemed focus on end-of-life environmental problems. The types of matters mentioned correspond to the concepts of reuse and substance hazard mitigation. Reuse's property is type which varies from recycling to remanufacture. Hazard mitigation's property of type had discrete dimensions of reduction and avoidance.

Potential Concepts: reuse (P: type D: recycling to remanufacture), Substance hazard mitigation (P: type D: reduction and avoidance)

Table 232: Summary of potential concepts, properties and dimensions for Pascual 2003

Concepts	Properties	Dimensions
Reuse	Type	Recycling to remanufacture
Substance hazard mitigation	Type	Reduction, avoidance

Coder	John Reap	Date	11/30/2008
Text Segment	Paragraphs 7-10	Type	Memo
Reference	Petrie, J. (2007). "New Models of Sustainability for the Resources Sector: A Focus on Minerals and Metals." *Process Safety and Environmental Protection* 85(1): 88-98.		

"…definition of sustainable development is taken here to mean the incorporation of ecological health, social harmony and economic efficiency…"

Sustainability is the primary theme of this paper, and in the first few paragraphs, the author provides his definition of it. In so doing, he provides the components property for sustainability and presents it alongside dimensions of ecological health, social harmony and economic efficiency.

Potential Concepts: sustainability (P: components D: ecological health, social harmony and economic efficiency)

Text Segment	Paragraphs 11	Type	Memo

"…appropriate to view sustainable use of mineral resources as one in which the rate of use equates to a fall-off in demand for its use."

In the 11th paragraph, resource consumption reduction comes to the fore. Implicit in the discussion about mineral resources is the dichotomy between renewable and nonrenewable resources; so, one can specify the property of type which varies between renewable or nonrenewable. The author introduces an interesting property for consumption of nonrenewable materials. He suggests measuring the rate of consumption on a dimensional scale more or less than demand deceleration. Substitution is mentioned as a strategy for resource consumption.

Potential Concepts: *Potential Concepts*: sustainability (P: components D: ecological health, social harmony and economic efficiency), resource consumption reduction (P: rate D: more or less than demand deceleration, P: substitution D: strategy)

Text Segment	Page 93-95	Type	Memo

The latter parts of the paper focus on frameworks and case studies. Few concepts directly related to environmental sustainability are present. However, the author's descriptions, tables and graphs point to the importance of resource consumption and reuse in the form of the recycling strategy.

Potential Concepts: *Potential Concepts*: sustainability (P: components D: ecological health, social harmony and economic efficiency), resource consumption reduction (P: rate D: more or less than demand deceleration; P: type D: renewable or nonrenewable; P: strategy D: substitution), reuse

Table 233: Summary of potential concepts, properties and dimensions for Petrie 2007

Concepts	Properties	Dimensions
Sustainability	Components	Ecological health, social harmony, economic efficiency
Resource consumption reduction	Rate	More or less than demand deceleration
	Type	Renewable or nonrenewable
	Strategy	Substitution
Reuse	Strategy	Recycling

Coder	John Reap	Date	12/??/2008
Text Segment	Article	Type	Memo
Reference	Phillips, H. and J. Thomas (1997). A Tale of Two Sites: Application of the Hewlett-Packard Self-assessment Procedure for Product Stewardship. Electronics and the Environment, 1997. ISEE-1997., Proceedings of the 1997 IEEE International Symposium on San Francisco, CA, IEEE.		

The article reviewed the application of an EBDM policy at Hewlett-Packard. Unfortunately, it did not communicate the specific recommendations for product design, manufacture, end-of-life or the supply chain. As a result, no codes related to the physical aspect of EBDM were obtained.

Table 234: Summary of potential concepts, properties and dimensions for Phillips 1997

Concepts	Properties	Dimensions

Coder	John Reap	Date	10/8/2008
Text Segment	Page 43, Para. 1-4	Type	Memo
Reference	Piwonka, D. T. (2001). Metals and Metal Manufacturing. WTEC Panel Report on Environmentally Benign Manufacturing. Baltimore, International Technology Research Institute: 43-53.		

"…major contributors to environmental problems from metal manufacturing are…lubricant aerosols and metal dust…casting effluents…spent sand solid waste…paint vapors…"

The author's initial summarization of the environmental problems in metal manufacture focuses on emissions. Emissions reduction is, therefore, the first concept that emerges in this book section.

Potential Concept: emission reduction

Text Segment	Page 44, Para. 5-11	Type	Memo

"Electrical consumption requirements are large…"

This section adds concern for resource consumption to the list of underlying concepts. The resource reduction concept is accompanied by the property of strategy. The author's statements in the 11th paragraph about setting energy and greenhouse gas reduction goals reveal that efficiency is the strategy of choice. The property dimension pair of strategy and efficiency also apply to emissions reduction.

Potential Concept: emission reduction (P: strategy D: efficiency), resource reduction (P: strategy D: efficiency)

Text Segment	Para. 12-16	Type	Memo

"Recycling of aluminum alloys…will increase over the next decade…"

Here, the author introduces the concept of reuse for the first time. It is accompanied by the strategy of material recycling.

Potential Concept: emission reduction (P: strategy D: efficiency), resource reduction (P: strategy D: efficiency), reuse (P: strategy D: material recycling)

Text Segment	Page 46 - end	Type	Memo

"…understanding of the thermodynamics of hazardous waste gas generation…"

The hazard avoidance concept surfaces in a bulleted list on page 46. As the quote indicates, the author focuses on hazardous gases, but other hazards are mentioned. A section on casting highlights efforts to eliminate toxic effluents and solid wastes, for instance. The same discussion introduces the strategy of substitution for hazard avoidance.

Potential Concept: emission reduction (P: strategy D: efficiency), resource reduction (P: strategy D: efficiency), reuse (P: strategy D: material recycling), hazard avoidance (P: strategy D: substitution)

Table 235: Summary of potential concepts, properties and dimensions for Piwonka 2001 #1

Concepts	Properties	Dimensions
Emission reduction	Strategy	Efficiency
Resource reduction	Strategy	Efficiency
Reuse	Strategy	Material recycling
Hazard avoidance	Strategy	Substitution

Coder	John Reap	Date	10/22/2008
Text Segment	Page 89-90, Para. 1-10	Type	Memo
Reference	Piwonka, D. T. (2001). Energy. WTEC Panel Report on Environmentally Benign Manufacturing. Baltimore, International Technology Research Institute: 89-95.		

"This reaction [combustion] produces carbon dioxide…that has been linked to global warming… Moreover, other hydrocarbon gases…have been shown to cause disease and degrade the environment."

Though written in the context of energy sources and environmental effects, this section contains two commonly encountered concepts. The author expresses concern about emissions and hazards related to emissions.

Potential Concept: emissions, hazards

Text Segment	Page 90, Para. 11-13	Type	Memo

"…supplies of carbon in forms that can be converted to energy are limited, and not necessarily located near users."

The author acknowledges the finite supply of fossil fuels in these paragraphs. More generally, these three paragraphs introduce the idea of limited resources, the concept of resource consumption.

Potential Concept: emissions, hazards, resource consumption

Text Segment	Page 90-91, Para. 14-15	**Type**	Memo

"There have been examples of highly efficient use of the energy generated from fossil fuels…"

One strategy for reducing resource consumption is energy efficiency. The author mentions a few examples of this dimension.

Potential Concept: emissions, hazards, resource consumption (P: strategy D: efficiency)

Text Segment	Page 91-end	**Type**	Memo

"…if the electrical energy…is generated by solar or wind energy, electric vehicles will actually be pollution-free."

The remainder of the article discusses different energy generation options. Notably, it discusses a few types of renewable energy sources as "free" and "pollution-free" sources of power. These statements clearly indicate that the author views the use of renewable energy sources as a strategy for emission and resource consumption reduction.

Potential Concept: emissions (P: strategy D: renewable energy sources), hazards, resource consumption (P: strategy D: efficiency, renewable energy sources)

Table 236: Summary of potential concepts, properties and dimensions for Piwonka 2001 #2

Concepts	Properties	Dimensions
Emissions	Strategy	Renewable energy sources
Hazards	?	?
Resource consumption	Strategy	Efficiency, renewable energy sources

Coder	John Reap	Date	12/18/2008
Text Segment	Article	Type	Memo
Reference	Pope, J., D. Annandale and A. Morrison-Saunders (2004). "Conceptualising sustainability assessment." *Environmental Impact Assessment Review* 24(6): 595-616.		

"Sustainability assessment is being increasingly viewed as an important tool…"

The authors spend the majority of this paper discussing the policy implications of a couple different approaches to assessing the sustainability of projects, programs and policies. They mention the property of <u>components</u> in the form of the triple bottom line and dimension them as <u>social, economic and environmental</u>. However, they contribute little in the way of physical guidance until the end of the paper.

At the close of the paper, they state that the concepts of <u>ecological integrity</u> and <u>resource consumption</u> are integral to any sustainable system. Ecological integrity appears next to biodiversity, but the authors seem to imply that <u>biodiversity</u> is a measure of integrity, making it a property that could vary dimensionally from <u>low to high</u>. Their list of sustainability principles ties the <u>strategy</u> of <u>efficiency</u> to resource consumption while differentiating <u>types</u> of resources which vary in a binary sense as <u>energy or materials</u>.

Table 237: Summary of potential concepts, properties and dimensions for Pope 2004

Concepts	Properties	Dimensions
Sustainability	Components	Social, economic and environmental
Ecological integrity	Biodiversity	Low to high
Resource consumption	Strategy	Efficiency
	Type	Energy or material

Coder	John Reap	Date	12/18/2008
Text Segment	Abstract – para. 9	Type	Memo
Reference	Reijnders, L. (2000). "A normative strategy for sustainable resource choice and recycling." *Resources, Conservation and Recycling* 28(1-2): 121-133.		

"…resource choice and recycling to meet the criterion of sustainability, defined as near constancy of natural resources."

Two concepts are evident in the abstract: reuse and sustainability. However, properties associated with these concepts set this paper apart. The presented quote and other statements seem to associate sustainability with the property of resource stocks which vary dimensionally from declining to growing. Reuse is ascribed the property of quality, which varies dimensionally from low to high and from economically fit to unfit. The author seems to equate a sustainability society with on in which resource stocks remain constant or grow. Preservation of resource quality and economic fitness through proper reuse is viewed as vital by the author.

Later in the introductory paragraphs the author also mentions the concept of emissions.

Potential Concepts: sustainability (P: resource stocks D: declining to growing), reuse (P: quality D: low to high, economically fit to unfit), emissions

Text Segment	Para. 8-	Type	Memo

"To maintain a (near) constant stock the usage of renewables should not substantially exceed the addition to stock."

These paragraphs introduce the concepts of resource consumption and renewable resources. For consumption, he adds the rate property which one may dimension as varying between <u>depleting and accumulating</u>. Renewable and nonrenewable resources cannot be used at a rate exceeding their accumulation for sustainable systems. He further observes that some renewable resources, flux based resources like the sun and wind, can be tapped to their maximum potential while stock based resources can only be drawn to the point of zero stock increase. Renewable resources gain the property of <u>type</u> which varies discretely between <u>flux or stock dependent</u>.

Potential Concepts: sustainability (P: resource stocks D: declining to growing), reuse (P: quality D: low to high, economically fit to unfit), emissions, resource consumption (P: rate D: depleting to accumulating), renewable resources (P: type D: flux or stock dependent)

Table 238: Summary of potential concepts, properties and dimensions for Reijnders 2000

Concepts	Properties	Dimensions
Sustainability	Resource stocks	Declining to growing
Reuse	Quality	Low to high
		Economically fit to unfit
Emissions	?	?
Resource consumption	Rate	Depleting to accumulating
Renewable resources	Type	Flux or stock dependent

Coder	John Reap	Date	7/26/2008
Text Segment	Para.: 19	Type	Memo
Reference	Ritzen, S. and C. Beskow (2001). "Actions for integrating environmental aspects into product development." *The Journal of Sustainable Product Design* 1(2): 91-102.		

"Decisions had been made regarding the exclusion of specific hazardous materials."

Unique among coded subject matter, this article deals with the process of adopting environmental guidance in companies. It is coded to identify the guidance considered worthy of adoption.

Concepts such as <u>hazardous substance minimization</u> and <u>life cycle</u> appear early in this article. The primary <u>strategy</u> for hazard minimization is <u>avoidance</u>. While not dimensioned, life cycle thinking is found to be important to all examined companies.

Potential Concepts: hazardous substance minimization (P: strategy D: avoidance), life cycle

Text Segment	Para.: 50	Type	Memo

"Company C was developing a methodology to perform environmental accounting."

The concept of <u>environmental cost</u> appears in this paragraph. For the first time, the authors mention the notion of assigning a monetary value to environmental costs. Properties and dimensions of this cost are not apparent.

Potential Concepts: hazardous substance minimization (P: strategy D: avoidance), life cycle, environmental cost

Table 239: Summary of potential concepts, properties and dimensions for Ritzen 2001

Concepts	Properties	Dimensions
Hazardous substance minimization	Strategy	Avoidance
Life Cycle	?	?
Environmental cost	?	?

Coder	John Reap	Date	11/30/2008
Text Segment	Page 198-199, paragraph 10-11	Type	Memo
Reference	Robèrt, K. H., B. Schmidt-Bleek, J. Aloisi de Larderel, G. Basile, J. L. Jansen, R. Kuehr, P. Price Thomas, M. Suzuki, P. Hawken and M. Wackernagel (2002). "Strategic sustainable development -- selection, design and synergies of applied tools." *Journal of Cleaner Production* 10(3): 197-214.		

"In the sustainable society, nature is not subject to systematically increasing…concentrations of substances extracted from the Earth's crust…substances produced by society…degradation by physical means…"

As with many other publications that incorporate the Natural Step, this one states its four sustainable system conditions. The first three system conditions deal with technology and the environment while the fourth deals with the socio-economic elements of sustainability. One must incorporate the first three into any effort to document the EBDM community's understanding of sustainability principles. The first two effectively call for reductions in emissions and hazards. The third states that the concept of ecosystem degradation is important.

The identified pages proceed to define properties for each concept contained in the system conditions. Efficiency is an important property for emissions and hazards that varies from low to high. Abundance is a property associated with emissions that also varies from low to high. The properties of biodegradability and persistence vary from low to high and are assigned to the hazards concept. Finally, the authors associate harvest rate and modification level with ecosystem degradation, and one can assign the dimensions of low to high to both. The authors support the hypothesis that a sustainable system is marked by efficient use of abundant, easily biodegradable resources with short residence times in the biosphere. These resources are harvested at a sufficiently low rate and in such a way as to not modify ecosystems.

Potential Concepts: emissions (P: efficiency D: low to high; abundance D: low to high), hazards (P: biodegradability D: low to high; P: efficiency D: low to high; P: persistence D: low to high), ecosystem degradation (P: harvest rate D: low to high; P: modification level D: low to high)

Text Segment	Page 200, paragraph 1-7	Type	Memo

"*Dematerialization*…means…*resource productivity*…and *less waste*…"

This set of paragraphs introduces the oft identified concept of <u>resource reduction</u>. The authors mention "resource productivity" in conjunction with this concept, which reveals the importance of the property of <u>efficiency</u>. The also emphasize <u>waste</u>, which also varies from <u>low to high</u>. And interestingly, they present <u>recycling</u> as a property of resource reduction. Many others treat reuse strategies separately.

Potential Concepts: emissions (P: efficiency D: low to high; abundance D: low to high), hazards (P: biodegradability D: low to high; P: efficiency D: low to high; P: persistence D: low to high), ecosystem degradation (P: harvest rate D: low to high; P: modification level D: low to high), resource reduction (P: efficiency D: low to high, P: waste D: low to high, P: recycling D: low to high)

Text Segment	Page 200, paragraph 3-7	Type	Memo

"*Dematerialization*…means…*resource productivity*…and *less waste*…"

A number of previously mentioned properties and concepts are reiterated in these paragraphs. However, one new property for resource reduction, service substitution, does emerge in the sixth paragraph. It varies dimensionally from low to high.

Potential Concepts: emissions (P: efficiency D: low to high; abundance D: low to high), hazards (P: biodegradability D: low to high; P: efficiency D: low to high; P: persistence D: low to high), ecosystem degradation (P: harvest rate D: low to high; P: modification level D: low to high), resource reduction (P: efficiency D: low to high, P: waste D: low to high, P: recycling D: low to high)

Text Segment	Page 206, paragraph 2-5	Type	Memo

"It is therefore essential to relate the flows, as well as the aspects and impacts of the LCA, to the utility unit of service. This is the rationale behind the concept Material Input Per unit Service (MIPS)"

In the later pages of the paper, one finds references to the life cycle concept. One also encounters another dimension for efficiency when considering resource reduction. The authors mention material input per unit service which varies dimensionally as low to high MIPS.

Potential Concepts: emissions (P: efficiency D: low to high; abundance D: low to high), hazards (P: biodegradability D: low to high; P: efficiency D: low to high; P: persistence D: low to high), ecosystem degradation (P: harvest rate D: low to high; P: modification level D: low to high), resource reduction (P: efficiency D: low to high, low to high MIPS, P: waste D: low to high, P: recycling D: low to high)

Table 240: Summary of potential concepts, properties and dimensions for Robèrt 2002

Concepts	Properties	Dimensions
Sustainability	?	?
Emissions	Efficiency	Low to high
	Abundance	Low to high
Hazards	Biodegradability	Low to high
	Persistence	Low to high
	Efficiency	Low to high
Ecosystem degradation	Harvest rate	Low to high
	Modification level	Low to high
Resource consumption	Efficiency	Low to high
		Low to high MIPS
	Waste	Low to high
	Recycling	Low to high
Life cycle	?	?

Coder	John Reap	Date	7/28/2008
Text Segment	Abstract	Type	Memo
Reference	Rossi, M., Scott Charon, Gabe Wing and James Ewell (2006). "Design for the Next Generation: Incorporating Cradle-to-Cradle Design into Herman Miller Products" *Journal of Industrial Ecology* 10(4): 193-210.		

"…DfE process generated a number of design changes…increasing recycled content…eliminating all PVC...designing the chair for rapid disassembly…and using materials with a green chemistry composition..."

Concepts commonly found in DfE literature are present in the abstract. These include reuse and hazardous material minimization. Both have the strategy property; reuse is dimensioned by recycling while hazard avoidance is dimensioned by white listing / process.

There seems to be more to reuse than explicitly stated in the abstract. Mentioning disassembly suggests that component reuse might be another strategy. Moreover, the authors claim to use cradle-to-cradle ideas in design which points to a richer set of properties and dimensions for reuse as well as other concepts.

Potential Concepts: reuse (P: strategy D: recycling), hazardous substance minimization (P: strategy D: white listing / process)

Text Segment	Page 194-196	**Type**	Memo

"…issued a challenge to manufacturers to change how they design products and to make them truly compatible with ecological systems."

Ecological compatibility is a broad concept that first appears in this section of text. Nutrient seems to be a closely related concept. The authors provide properties such as type and safety for this concept. Type's dimensions are biological or technical. Safety varies from dangerous to safe. According to the authors, ecological compatibility hinges upon using safe biological and technical nutrients in products.

The life cycle and resource reduction concepts are also mentioned. Strategy and type are properties of resource reduction dimensioned by waste minimization and energy or material, respectively.

Potential Concepts: ecological compatibility, nutrient (P: type D: biological or technical; P: safety D: dangerous to safe), life cycle

Text Segment	Page 200-202	Type	Memo

"Can the component be separated as a homogeneous material..."

The discussion on these pages adds depth to our understanding of the reuse concept. Composting is cited as a reuse strategy. We learn that the properties of separation and identification influence reuse. Both vary from simple to difficult. The difference between a purely closed loop material cycle for a given product and one that involves reuse in a different type of product appears. This leads to the completeness property of reuse which varies from partial to complete.

The authors also mention infrastructure for recycling. One might call it a property of reuse, but I believe cycling infrastructure can stand as an independent property related to reuse. Other authors have mentioned a number of properties that one could use to define such infrastructure.

Potential Concepts: reuse (P: strategy D: recycling, composting; P: separation D: simple to difficult; P: identification D: simple to difficult; P: completeness D: partial to complete), infrastructure

Table 241: Summary of potential concepts, properties and dimensions for Rossi 2006

Concepts	Properties	Dimensions
Reuse	Strategy	Recycling
	Identification	Easy to difficult
	Separation	Easy to difficult
	Completeness	Partial to complete
Hazardous Substance Minimization	Strategy	White listing / process
Ecological compatibility	?	?
Nutrient	Type	Biological or technical
	Safety	Dangerous to safe
Life cycle	?	?
Resource reduction	Strategy	Waste minimization
	Type	Energy or material
Cycling infrastructure	?	?

Coder	John Reap	Date	12/17/2008
Text Segment	Abstract – para. 4	Type	Memo
Reference	Sandholzer, D. and M. Narodoslawsky (2007). "SPIonExcel-Fast and easy calculation of Sustainable Process Index via computer." *Resources Conservation and Recycling* 50: 130-142.		

"Sustainable Process Index (SPI)…is based on the assumption that a sustainable economy builds only on solar radiation as natural income."

The abstract and first few paragraphs discuss the <u>life cycle</u> concept. When the authors transition to their discussion about SPI, another concept, <u>renewable resources</u>, emerges. The quoted statement about a solar economy is another way of prescribing the use of renewable resources as a partial cure to the problem of sustainability.

Potential Concepts: life cycle, renewable resources

Text Segment	Para. 5 - 14	Type	Memo

"…the total area A_{tot} for sustainable embedding of human activities…into the ecosphere is calculated…"

Here, one sees statements about the commonly stated concepts of <u>resource consumption</u> and <u>emissions</u>, but one also sees unique dimensions for each. The authors provide areas needed to provide material and energy resources and dissipate emissions. Here, material resources also refer to land resources. The provide area factors for renewable materials, fossil materials, energy production, builds and more. One might then ascribe the property of <u>level</u> with the dimension of <u>area</u> to each concept.

Potential Concepts: life cycle, renewable resources, resource consumption (P: level D: area), emissions (P: level D: area)

Text Segment	Para. 15-16	Type	Memo

"…the 'cost' in terms of ecological sustainability of this particular good or service…"

The authors use the previously mentioned area dimensions to better define the sustainability concept. Ascribing the property of degree to sustainability, one can dimension it using low to high SPI.

Potential Concepts: life cycle, renewable resources, resource consumption (P: level D: area), emissions (P: level D: area), sustainability (P: degree D: low to high SPI)

Table 242: Summary of potential concepts, properties and dimensions for Sandholzer 2007

Concepts	Properties	Dimensions
Life cycle	?	?
Renewable resources	?	?
Resource consumption	Level	Area
Emissions	Level	Area
Sustainability	Degree	Low to high SPI

Coder	John Reap	Date	8/25/2008
Text Segment	Article	Type	Memo
Reference	Segars, J.W., S.L. Bradfield, J.J. Wright and M.J. Realff (2003). EcoWorx, Green Engineering Principles in Practice. *Environmental Science & Technology* 37(23): 5269-5277.		

"…analysis of the EcoWorx system demonstrated the value of the 12 Principles in verifying and formalizing the experience and intuition of product designers."

This article presents an analysis of a carpet tile system using a framework established by the 12 Principles of Green Engineering. Abstracting away from the details of the application, one sees that the principles stated in the article's first table contain its primary concepts. Consumption reduction is the concept at the heart of at least four of the 12 principles. It has properties of type and strategy. Type has dimensions of material or energy, while strategy includes waste minimization and efficiency. Reuse factors into three of the stated principles. Its strategy property has dimensions ranging from recycling to product reuse. This article also suggests that reuse also has the properties of infrastructure and material diversity. Material diversity varies low to high while infrastructure varies along dimensions of connectivity and compatibility. Hazard avoidance is the first of the twelve principles, and its strategy property has dimensions of reduction, elimination and substitution. The final principle introduces the concept of renewable resources which has the property of type and dimensions of energy or material.

Potential concepts: consumption reduction (P: type D: material or energy; P: strategy D: waste min. and efficiency), reuse (P: strategy D: recycling to product reuse; P: infrastructure D: Separate to connected, D: incompatible to compatible; P: material diversity D: Low to high), hazard avoidance (P: strategy D: reduction, elimination and substitution), renewable resources (P: type D: energy or material)

Table 243: Summary of potential concepts, properties and dimensions for Segars 2003

Concepts	Properties	Dimensions
Consumption reduction	Type	Material or energy
	Strategy	Waste min. and efficiency
Reuse	Strategy	Recycling to product reuse
	Infrastructure	Separate to connected
		Incompatible to compatible
	Material diversity	Low to high
Hazard avoidance	Strategy	Reduction, elimination and substitution
Renewable resources	Type	Energy or material

Coder	John Reap	Date	9/30/2008
Text Segment	Abstract	Type	Memo
Reference	Seliger, G., H-J. Kim, S. Kernbaum and M. Zettl. (2008). "Approaches to sustainable manufacturing" *International Journal of Sustainable Manufacturing* 1(1): 58-77.		

"Environmental regulations for technical products currently focus on recycling ratios and prohibition of toxic materials...creating more use-productivity with less resource consumption has considerable potential..."

Reuse, hazard avoidance and resource reduction concepts are present from the beginning in the authors' text. The reuse strategy of recycling is in the abstract next to the resource reduction strategy of use phase productivity. One hazard avoidance strategy mentioned in the abstract is toxic material prohibition. Sustainability is clearly a recurrent theme, but properties and dimensions for this concept are not present in the abstract.

Potential Concepts: resource reduction (P: strategies D: use phase productivity), reuse (P: strategy D: recycling), hazard avoidance (P: strategy D: toxic material prohibition), sustainability.

Text Segment	Para. 1-8	Type	Memo

"…sustainable manufacturing started to focus on waste reduction...reduction of resources and energy use in production."

These paragraphs add the type property to the resource reduction concept and dimension it with energy or material. They also add multiple dimensions to existing properties. Resource reduction strategies such as waste reduction, efficiency, utilization ratio, life span extension appear. Hazard reduction gains the dimension of toxic reduction. Reuse adds the product reuse and remanufacturing strategies. With the exception of life span extension and utilization ratio, these strategies have been encountered elsewhere.

The author introduces an idea of sustainable global development that might be implicit in previously coded papers. One might best describe his concept as resource decoupling. As described, living standards increase exponentially while resource demands remain flat or increase with only a shallow slope. The possibility of achieving this behavior hinges on the property of use-productivity which varies from low to high.

The remainder of the paper presents brief overviews of technologies that embody some of the concepts found on the first few pages.

Potential Concepts: sustainability, resource reduction (P: type D: energy or material; P: strategies D: use phase productivity, waste reduction, efficiency, utilization ratio, life span extension), reuse (P: strategy D: recycling, remanufacture, product reuse), hazard avoidance (P: strategy D: toxic material prohibition, toxic reduction), resource decoupling (P: use-productivity D: low to high).

Table 244: Summary of potential concepts, properties and dimensions for Seliger 2008

Concepts	Properties	Dimensions
Resource reduction	Strategies	Use phase productivity, waste reduction, efficiency, utilization ratio, life span extension
	Type	Material or energy
Sustainability	?	?
Reuse	Strategy	Recycling, , remanufacture, product reuse
Hazard avoidance	Strategy	Toxic material prohibition, toxic reduction
Resource decoupling	Use-productivity	Low to high

Coder	John Reap	Date	11/15/2008
Text Segment	Abstract	Type	Memo
Reference	Shastri, Y., U. Diwekar, H. Cabezas and J. Williamson (2008). "Is Sustainability Achievable? Exploring the Limits of Sustainability with Model Systems." *Environ. Sci. Technol.* 42(17): 6710-6716.		

"…different dimensions of sustainability..."

The sustainability concept is the central theme in the abstract. The author notes that it has the property of elements which is dimensioned by social, economic and environmental. This relationship is commonly observed in EBDM and environmental policy literature. However, his second property for sustainability, Fisher information, is unique. Dimensions for this interesting property do not appear in the abstract.

Potential Concepts: sustainability (P: elements D: social, economic and environmental; P: Fisher information D: ?)

Text Segment	Para. 1-3	Type	Memo

"…the industrial revolution, has led to severe depletion and deterioration of the Earth's natural resources."

The early paragraphs of the introduction bring resource consumption to the fore. This commonly encountered concept is central to the author's piece, and it is not surprising that it appears early.

Potential Concepts: sustainability (P: elements D: social, economic and environmental; P: Fisher information D: ?), resource consumption

Text Segment	Para. 4-6	Type	Memo

"…environmental services...relevant for the economic processes such as resource extraction, waste assimilation, recycling, and pollution."

In these few paragraphs, the author introduces a theme related to resource consumption. The concept of <u>environmental services</u> is the less tangible counterpart to the environmental resources concept. Each of the activities named in the quote could be considered a property of the environmental service concept, and each could vary dimensionally from <u>low to high</u>. Only pollution fails to fit this pattern. It is difficult to think of pollution as an environmental service, and the author's decision to group it with properties such as <u>resource provision</u>, <u>waste assimilation</u> and <u>recycling</u> is somewhat puzzling.

Potential Concepts: sustainability (P: elements D: social, economic and environmental; P: Fisher information D: ?), resource consumption, environmental services (P: resource provision D: low to high; P: waste assimilation D: low to high; P: recycling D: low to high)

Text Segment	Para. 21-22	Type	Memo

"…FI [Fisher Information] based sustainable regime hypothesis states that the time-averaged Fisher Information of a system in a persistent regime does not change with time."

In these paragraphs, one finds a dimension for sustainability's Fisher information property. Specifically, one sees that the author believes it varies between <u>steady and dynamic</u>. He attributes a time-averaged change with an unsustainable system. So, his hypothesis is that sustainable systems exhibit steady Fisher information levels.

Potential Concepts: sustainability (P: elements D: social, economic and environmental; P: Fisher information D: steady to dynamic), resource consumption, environmental services (P: resource provision D: low to high; P: waste assimilation D: low to high; P: recycling D: low to high)

Table 245: Summary of potential concepts, properties and dimensions for Shastri 2008 #1

Concepts	Properties	Dimensions
Sustainability	Elements	Social, economic and environmental
	Fisher Information	Steady to dynamic
Resource consumption	?	?
Environmental services	Resource provision	Low to high
	Waste assimilation	Low to high
	Recycling	Low to high

Coder	John Reap	Date	11/15/2008
Text Segment	Abstract – para. 4	Type	Memo
Reference	Shastri, Y., U. Diwekar and H. Cabezas (2008). "Optimal Control Theory for Sustainable Environmental Management." *Environ. Sci. Technol.* 42(14): 5322-5328.		

"…human activities on planet Earth has led to sever depletion and deterioration of natural resources."

The early paragraphs emphasize <u>resource consumption</u>. It plays a central role in the optimization problem encountered in later paragraphs. The <u>sustainability</u> concept is also present in the beginning, and he assigns it two properties: <u>elements</u> and <u>Fisher information</u>. The elements of sustainability, <u>social, environmental and ecological</u>, dimension the property.

Potential Concepts: resource consumption, sustainability (P: elements D: social, economic and environmental; P: Fisher information D: ?)

Text Segment	Para. 6-7	Type	Memo

"…sustainability hypothesis states that the time-averaged Fisher Information of a system in a persistent (sustainable) regime does not change with time."

In these paragraphs, one finds a dimension for sustainability's Fisher information property. Specifically, one sees that the author believes it varies between <u>steady and dynamic</u>. He attributes a time-averaged change with an unsustainable system. So, his hypothesis is that sustainable systems exhibit steady Fisher information levels.

Potential Concepts: resource consumption, sustainability (P: elements D: social, economic and environmental; P: Fisher information D: steady to dynamic)

Table 246: Summary of potential concepts, properties and dimensions for Shastri 2008 #2

Concepts	Properties	Dimensions
Sustainability	Elements	Social, economic and environmental
	Fisher Information	Steady to dynamic
Resource consumption	?	?

Coder	John Reap	Date	7/23/2008
Text Segment	Article	Type	Memo
Reference	Shiovitz, A. and E. Craig (1997). Using data to determine design for environment product goals. Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment San Francisco, CA, USA, IEEE.		

"…Sun's three DFE focus areas...energy efficiency, design for recovery, reuse, recycling, and reducing substances of concern…"

This passage from the abstract captures the main environmental concepts in this article. Concepts such as resource reduction, reuse and hazardous material reduction dominate. The property of type with the dimension of energy applies to resource reduction. Reuse's property of type varies from recycling to product recovery. Properties of strategy and life cycle stage apply to resource reduction and hazardous material reduction. In both cases strategy varies discretely by avoidance or efficiency, and life cycle stage varies from design to end-of-life.

Table 247: Summary of potential concepts, properties and dimensions for Shiovitz 1997

Concepts	Properties	Dimensions
Resource reduction	Type	energy
	Strategy	Avoidance or efficiency
	Life cycle stage	Design to end-of-life
Reuse	Type	Recycling to product recovery
Hazardous material reduction	Strategy	Avoidance or efficiency
	Life cycle stage	Design to end-of-life

Coder	John Reap	Date	9/15/2008
Text Segment	Article	Type	Memo
Reference	Shonnard, D.R., A. Kicherer and P. Saling. (2003). Industrial Applications Using BASF Eco-Efficiency Analysis: Perspectives on Green Engineering Principles. *Environmental Science & Technology* 37: 5340-5348.		

"…major elements of the environmental assessment include primary energy use, raw materials utilization, emissions to all media, toxicity, safety risk, and land use."

The paper's concepts appear in the first three pages and largely correspond to those encountered in other EBDM literature. Resource reduction and hazard avoidance capture the ideas present in the passage and the paper's first three pages. The property of type describes the resources that one should reduce; its dimensions include energy, material and land. Land is a new addition to the usual dimensional space for the resource reduction concept. Hazards also have types, and the dimensions of toxicity and other safety hazards slightly expand its range.

Potential concepts: resource reduction (P: type D: energy, material and land), hazard avoidance (P: type D: toxicity, other safety hazard)

Table 248: Summary of potential concepts, properties and dimensions for Shonnard 2003

Concepts	Properties	Dimensions
Resource reduction	Type	Energy, material, land
Hazard avoidance	Type	Toxicity and other safety hazard

Coder	John Reap	Date	12/21/2008
Text Segment	Article	Type	Memo
Reference	Söderman, Ljunggren M. (2003). "Including indirect environmental impacts in waste management planning." *Resources, Conservation and Recycling* 38(3): 213-241.		

"…waste management solutions for Sweden…include…recovering power, heat, biogas, materials and nutrients…"

Soderman's paper focuses on the concept of reuse. It primarily provides strategies that better inform the reader about this concept. Introduced strategies appear in the quoted citation: energy recovery, heat, anaerobic digestion, recycling and composting / fertilizer production. The rest of the paper analyzes the different global warming potentials for these strategies.

Table 249: Summary of potential concepts, properties and dimensions for Söderman 2003

Concepts	Properties	Dimensions
Reuse	Strategy	Power recovery
		Heat
		Anaerobic digestion
		Material recycling
		Composting / fertilizer production

Coder	John Reap	Date	10/9/2008
Text Segment	Article	Type	Memo
Reference	Sutherland, J. (2001). Environmental Issues of the Automotive Industry. WTEC Panel Report on Environmentally Benign Manufacturing. Baltimore, International Technology Research Institute: 62-78.		

Most of the common EBDM concepts found during the coding of other sources appear in the first third of Sutherlands report. One sees: reuse, life cycle, hazard avoidance, bio-compatibility, resource consumption and emission reduction. Strategy is a property for concepts such as reuse, hazard avoidance, resource consumption and emissions reduction. For reuse, strategy's dimensions vary from material recycling to product reuse; material number minimization is another strategy. Properties such as infrastructure, which varies dimensionally from linear to cyclical, and cycle number, which varies from low to high, also give definition to reuse. Hazard avoidance strategies focus on the reduction, substitution or elimination of toxic materials and emissions during all phases of an automobiles life cycle. The primary resource consumption strategy found in this article is efficiency improvement. This applies to automobile production phases as well as the all important use phase. The emissions reduction strategy mentioned at multiple times in multiple forms was waste minimization.

Potential Concept: emission reduction, hazard avoidance (P: strategy D: reduction, substitution or elimination), life cycle, resource consumption (P: strategy D: efficiency), bio-compatibility, reuse (P: strategy D: material recycling to product reuse, material number minimization; P: infrastructure D: linear to cyclical; P: cycle number D: low to high)

Table 250: Summary of potential concepts, properties and dimensions for Sutherland 2001

Concepts	Properties	Dimensions
Emission reduction	Strategy	Waste minimization
Resource consumption reduction	Strategy	Efficiency
Reuse	Strategy	Material recycling to product reuse
		Material number minimization
	Infrastructure	Linear to cyclical
	Cycle number	Low to high
Hazard avoidance	Strategy	Substitution, reduction, elimination
Bio-compatibility	?	?
Life cycle	Phase	Material extraction to end of life

Coder	John Reap	Date	7/22/2008
Text Segment	Article	Type	Memo
Reference	Szczerbicki, E. and M. Drinkwater (2004). "Concurrent Engineering Design for Environment." *Cybernetics and Systems* 35: 667-681.		

"DfE includes designing for recyclability, reusability, durability and maintainability…also promotes the reduction of energy consumption and product emissions…"

As the quote from the abstract suggests, the article centers on three concepts: <u>reuse</u>, <u>resource minimization</u> and <u>waste reduction</u>. Reuse has the property of <u>type</u> which varies dimensionally from <u>recycling to product reuse</u>.

Resource minimization focuses on product design in this article. One might say it has the property of <u>product strategy</u> which varies between durability and maintainability. However, durability and ease of maintenance are not mutually exclusive. Instead, it seems better to class these ideas in separate dimensional ranges. A product strategy could vary from <u>durable to disposable</u> and from <u>easy to difficult to maintain</u>. The author clearly argues that one minimizes resource usage by following a product strategy that promotes durability and ease of maintenance. Resource minimization also has the property of <u>type</u> which can be either <u>material or energy</u>.

Potential Concepts: reuse (P: type D: recycling to product reuse), resource minimization (P: product strategy D: durable to disposable, D: easy to difficult to maintain; P: type D: material or energy)

Table 251: Summary of potential concepts, properties and dimensions for Szczerbicki 2004

Concepts	Properties	Dimensions
Reuse	Type	Recycling to product reuse
Resource Minimization	Type	Material or energy
	Product strategy	Durable to disposable
		Easy to difficult to maintain

Coder	John Reap	Date	7/10/2008
Text Segment	Paragraphs: abstract – paragraph 5	Type	Memo
Reference	Telenko, C., C.C. Seepersad, M.E. Webber (2008) "A Compilation of Design for Environment Principles and Guidelines" *ASME International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, Aug. 3-6, New York City, New York, USA. [Paper Number: 49651]		

"…most powerful and well-known tool within DfE…," LCA, "…is a retrospective design tool..."

Design for environment guidance (<u>DfE guidance</u>) is the authors' overarching concept, and it is prominent in the opening paragraphs. Different forms of DfE guidance occur before, during and after the primary design phases of conceptual and embodiment design. The provided quote highlights one dimension of this <u>timing</u> property. The authors provide a dimensional range for timing varying from concurrent to retrospective. The provided range seems too restrictive to me. One might enter a design process knowing that certain choices will not be preferable under any circumstances. Therefore a more complete dimensional range would be from <u>apriori</u> to <u>retrospective</u>. Guidance possesses the property of <u>focus</u> which ranges from individual <u>design phases to the entire product life cycle</u>. Finally, the authors also observe that DfE guidance appears in more and less abstract forms. This property of <u>abstraction</u> varies in two senses. Some guidance clearly relates to specific product features and components while other guidance is broadly applicable; it varies from <u>concrete to abstract</u>. Guidance also varies between <u>qualitative and quantitative</u>.

Potential Concepts: DfE guidance (P: timing D: apriori to retrospective; P: focus D: design phase to life cycle; P: abstraction D: concrete to abstract, D: qualitative to quantitative)

Text Segment	Paragraphs: 21-24; 38-40	Type	Memo

"Principle A aims to address resource depletion by encouraging reuse of resources…and renewability of consumed resources, such as energy."

Reuse is the first concept present in these paragraphs and the associated table. The authors mention reuse in the context of basic materials and components; in other words, they focus on traditional recycling and remanufacturing. For them, reuse's main property is type which varies from recycling to remanufacturing. Difficulty, a second property of reuse, receives the bulk of the attention in these paragraphs. It varies dimensionally from material homogeneity to material heterogeneity and from separable to integral. It is the author's contention that one facilitates reuse by enhancing material homogeneity and seprability in products.

Renewable resources stand as the second major concept in these paragraphs. It refers broadly to both material and energy resources.

Potential Concepts: Renewable resources, Reuse (P: type D: recycling to remanufacturing; P: difficulty D: homogeneity to heterogeneity, D: separable to integral)

Text Segment	Paragraphs: 25-27	Type	Memo

"…principle requires elimination of hazardous substances and pollutants as well as the conversion of waste to useful materials for products and ecosystems."

The authors list guidelines meant to avoid, reduce and contain hazardous substances. The concept that appears is one of substance hazard mitigation, which has the property type and the discrete dimensions of avoidance, reduction and containment.

In these paragraphs, one notes an expansion of the dimensional range for reuse. Reuse by ecosystems is seen as acceptable; so, the dimensions of reuse range from biodegradation to remanufacturing. Use of biodegradation suggests a concept not explicit in the authors' work – system coupling. When biodegradation becomes an explicit part of one's product design plan, one intentionally couples product and natural systems.

Potential Concepts: System coupling, Substance hazard mitigation (P: type D: avoidance, reduction, containment), Reuse (P: type D: biodegradation to remanufacturing; P: difficulty D: homogeneity to heterogeneity, D: separable to integral)

Text Segment	Paragraphs: 28-34	Type	Memo

"Ensure minimal use of resources..."

Resource minimization is the key concept in these paragraphs. Taking a distinctly life cycle perspective, the authors focus first on production and then product use. Its properties seem to be avoidance, efficiency and waste prevention. Avoidance varies from process to material elimination. Efficiency and waste prevention share the dimensions of mass or energy and process to product improvement.

Additionally, they note the value of utilizing flows of energy and materials generated by products and mention the potential benefits of interconnecting these flows. This is a form of reuse; it adds the dimension of <u>energy or material</u> to the reuse concept.

Potential Concepts: Resource minimization (P: Avoidance D: process to material elimination; P: Efficiency D: material or energy, D: process or product improvement; P: waste prevention D: material or energy, D: process or product improvement), Reuse (P: type D: biodegradation to remanufacturing, D: energy or material; P: difficulty D: homogeneity to heterogeneity, D: separable to integral)

Text Segment	Paragraphs: 35-37	Type	Memo

"…principle requires elimination of hazardous substances and pollutants as well as the conversion of waste to useful materials for products and ecosystems."

Many ideas in this set of paragraphs correspond to previously stated concepts such as reuse and resource minimization. These ideas include system disassembly, part reutilization and upgrading for efficiency. <u>Durability</u> is unique to this set of paragraphs. The properties of durability include <u>maintenance</u>, which varies from <u>low to high</u> and <u>simple to difficult</u>, <u>aesthetic appeal</u>, which varies between <u>trendy and timeless</u>, and <u>cleanliness</u>, which varies from <u>easily cleaned to readily soiled</u>. The authors state clearly that timeless products requiring little easily performed maintenance that clean easily are durable and environmentally preferable.

Potential Concepts: durability (P: maintenance D: low to high, D: simple to difficult; P: aesthetic appeal D: trendy to timeless; P: Cleanliness D: easily cleaned to readily soiled)

Table 252: Summary of potential concepts, properties and dimensions for Telenko 2008

Concepts	Properties	Dimensions
DfE guidance	Timing	Apriori to retrospective
	Focus	Design phase to life cycle
	Abstraction	Concrete to abstract
		Qualitative to quantitative
Reuse	Type	Biodegradation through recycling to remanufacturing
		Energy or material
	Difficulty	Homogeneity to heterogeneity
		Separable to integral
Renewable resources	?	?
System coupling	?	?
Substance hazard mitigation	Type	Avoidance, reduction and containment
Resource minimization	Avoidance	Process to material elimination
	Efficiency	Mass or energy
		Process or product improvement
	Waste Reduction	Mass or energy
		Process or product improvement
Durability	Maintenance	Low to high
		Simple to difficult
	Aesthetic appeal	Timeless to trendy
	Cleanliness	Easily cleaned to readily soiled

Coder	John Reap	Date	9/7/2008
Text Segment	Abstract – page 228	Type	Memo
Reference	Templet, P. (1999). "Energy, diversity and development in economic systems; an empirical analysis." *Ecological Economics* 30: 223-233.		

"As diversity increases the efficiency of generating outputs with a given amount of energy also increases."

While rooted in economics, this paper discusses resource consumption. The author writes about resource consumption in terms of economic units produced per unit or resources consumed, and he focuses on energy resources. His numerous statements linking economic efficiency with sustainability reveal the presence of the resource consumption reduction concept. Properties such as strategy and type are dimensioned by efficiency and energy or material, respectively.

Diversity is repeatedly mentioned as a means of raising economic efficiency. The clear link with efficiency shows that the previously mentioned coding structure incorporates it, but its importance in the paper suggests that diversity could stand as an independent concept.

Potential Concepts: diversity, resource consumption reduction (P: strategy D: efficiency; P: type D: energy or material)

Text Segment	Page 229-233	Type	Memo

"...changes in development capacity can occur by two distinct means: increasing energy consumption (growth) or increasing system diversity (development)."

Later pages discuss the economic development concept. They primarily discuss its strategy property, though rate also appears. Strategy is dimensioned by either energy consumption or system diversity while rate varies from low to high.

The closing pages also contain comments that reinforce the decision to maintain diversity as an independent concept. In fact, the author's closing statement lists diversity separate from efficiency as one of the conditions for sustainability.

Potential Concepts: economic development (P: strategy D: energy consumption or system diversity; P: rate D: low to high)

Table 253: Summary of potential concepts, properties and dimensions for Templet 1999

Concepts	Properties	Dimensions
Diversity	?	?
Resource consumption reduction	Strategy	Efficiency
	Type	Energy or material
Economic development	Strategy	Energy consumption or system diversity
	Rate	Low to high

Coder	John Reap	Date	10/8/2008
Text Segment	Article	Type	Memo
Reference	Thurston, D.T. and B. Bras (2001). Chapter 4: Systems Level Issues. WTEC Panel Report on Environmentally Benign Manufacturing. Baltimore, International Technology Research Institute: 31-42.		

Three concepts appear in this article that influence environmental design guidance. Two, reuse and resource reduction, appear in many other articles. The third, environmental synchronization, is far less common. Reuse has the strategy property which exhibits dimensions of material recycling to product reuse. This theme is prevalent during discussions of product take-bake legislation, selling services and economic benefits of green engineering. Resource reduction has properties of strategy and type which have dimension of conservation and waste reduction and material or energy, respectively. This concept appears when the authors first discuss corporate design for environment initiatives. As presented, resource reduction is the primary objective of these initiatives.

Environmental synchronization occurs in a single paragraph. Unlike many of the other statements which deal with reuse and reduction, this paragraph focuses on using materials that the biosphere can accept and biodegrade. Now that I think of it, this is an important concept in EBDM. I am surprised that it is not found in more memos.

Table 254: Summary of potential concepts, properties and dimensions for Thurston 2001

Concepts	Properties	Dimensions
Reuse	Strategy	Material recycling to product reuse
Resource reduction	Strategy	Conservation, waste reduction
	Type	Material or energy
Environmental synchronization	?	?

Coder	John Reap	Date	12/17/2008
Text Segment	Article	Type	Memo
Reference	Tyteca, D. (1998). "Sustainability Indicators at the Firm Level." *Journal of Industrial Ecology* 2(4): 61-77.		

Tyteca mentions the concept of sustainability, and then, he introduces the idea of productive efficiency. Now, this idea quickly leads to a simple ratio of desirable and undesirable inputs and outputs to and from an industrial subsystem operating in an economy. From the perspective of environmental sustainability, his ratio captures two concepts of interest: resource consumption and emissions. Resource consumption has the property of type which has dimensions of either energy or material.

Table 255: Summary of potential concepts, properties and dimensions for Tyteca 1998

Concepts	Properties	Dimensions
Sustainability	?	?
Resource consumption	Type	Energy or material
Emissions	?	?

Coder	John Reap	Date	7/23/2008
Text Segment	Article	Type	Memo
Reference	Ufford, D. A. and W. J. Ward (1999). Next generation design for the environment paradigms. Electronics and the Environment, Danvers, MA, IEEE.		

"…most significant paradigm shift has been engineering accepting…the responsibility that hazardous materials and product / process wastes are design defects."

The abstract contains the focal environmental concepts in the article. The authors primarily discuss efforts associated with hazardous material reduction and resource reduction. Hazard reduction has the property of strategy which seems to be narrowly dimensioned as substitution. Resource reduction's property is strategy, and its dimension is waste minimization.

Table 256: Summary of potential concepts, properties and dimensions for Ufford 1999

Concepts	Properties	Dimensions
Resource reduction	Strategy	Waste minimization
Hazardous material reduction	Strategy	Substitution

Coder	John Reap	Date	10/20/2008
Text Segment	Page 4, Para. 1-2	Type	Memo
Reference	U.S. Congress, Office of Technology Assessment, *Green Products by Design: Choices for a Cleaner Environment, OTA-E541* (Washington, DC: U.S. Government Printing Office, October 1992): 4-10.		

"…most visible impact is municipal solid waste (MSW)."

The executive summary of this classic government document discusses product design's place in the broader context of environmental issues. The first paragraph highlights interest in the concept of <u>emissions</u> when it discusses the ubiquity and public awareness of municipal solid waste.

Potential Concepts: emissions

Text Segment	Page 4-5, Para. 3-4	Type	Memo

"U.S. industry generates some 700 million tons of hazardous waste…"

The concept of <u>hazard avoidance</u> appears shortly after the paragraphs focusing on general emissions. The appearance of the concept takes the form of a discussion about hazardous wastes and toxic products such as pesticides, solvents and fuels.

Potential Concepts: emissions, hazard avoidance

Text Segment	Page 6-8, Para. 6-end	Type	Memo

"…green design involves two general goals: waste prevention and better material management…"

Though given different names, the sections goals for green design correspond with the concepts of <u>resource consumption</u> and <u>reuse</u>. <u>Strategy</u> is a property of both, and both vary dimensionally by strategy. For resource consumption, the text mentions efficiency, life extension and waste minimization. Reuse's dimensions include material recycling to remanufacture, composting and energy recovery.

Potential Concepts: emissions, hazard avoidance, resource consumption (P: strategy D: efficiency, life extension, waste minimization), reuse (P: strategy D: material recycling to remanufacture, composting, energy recovery)

Table 257: Summary of potential concepts, properties and dimensions for U.S. Congress 1992 #1

Concepts	Properties	Dimensions
Emissions	?	?
Hazard avoidance	?	?
Resource consumption	Strategy	Efficiency
		Life extension
		Waste minimization
Reuse	Strategy	Material recycling to remanufacture
		Composting
		Energy recovery

Coder	John Reap	Date	10/20/2008
Text Segment	Page 53, Para. 1-3	Type	Memo
Reference	U.S. Congress, Office of Technology Assessment, *Green Products by Design: Choices for a Cleaner Environment, OTA-E541* (Washington, DC: U.S. Government Printing Office, October 1992): 53-63.		

"…networks impose constraints on the designer that have important implications when attempting to integrate environmental objectives..."

The introductory paragraphs place product design in the context of production and consumption networks. The authors think these networks constrain product design in technical, economic and environmental ways. Though not stated explicitly, absence of recycling infrastructure constrains a designer's ability to reduce product impact via features valuable and end-of-life. For instance, designing for disassembly may add cost without adding any benefit if a recycling infrastructure does not exist. So, the first sections introduce the concept of <u>network constraints</u>.

Potential Concepts: network constraints

Text Segment	Page 53-55, Para. 4-9	Type	Memo

"Designers might ask questions [about]…waste streams…substitutes for toxic constituents…recyclability…"

When taking a "product-oriented" approach to green engineering, the authors believe designers commonly ask a particular set of questions. The content of these questions reveals the green design goals in the minds of the authors. As the quote indicates, concepts such as <u>emissions</u>, <u>hazard avoidance</u> and <u>reuse</u> dominate their thinking. Hazard avoidance comes with a property and dimension couple – <u>strategy</u> and <u>substitution</u>. Later, efficiency improvements are discussed in the context of reducing emissions which makes <u>efficiency</u> a dimension of the <u>strategy</u> property of emission reduction.

Potential Concepts: network constraints, emissions (P: strategy D: efficiency), hazard avoidance (P: strategy D: substitution), reuse

Text Segment	Page 55-57, Para. 10-15	Type	Memo

"…waste streams be used as process inputs…"

As they transition from descriptions of product centered to production centered approaches to green engineering, two new ideas appear. First, they mention the <u>life cycle</u> concept. It first appears as part of a question asked by those seeking to engineer green production and consumption systems, not simply products in those systems. The second idea is "waste equals food." A question about using industrial waste outputs as inputs for other processes leads one to see that the structure of production and consumption networks can be the target of design engineering. <u>Structure</u>, in this context, is a property of networks which varies dimensionally from <u>linear to cyclic</u>.

This type of thinking has the effect of changing network constraints concept identified in the introduction. <u>Constraints</u> are properties of networks if one takes this view.

Potential Concepts: network (P: constraints D: ?; P: structure D: linear to cyclic), emissions (P: strategy D: efficiency), hazard avoidance (P: strategy D: substitution), reuse

Text Segment	Page 57-58, Para. 16-22	Type	Memo

"…ultimate extension of the manufacturer take-back concept is the 'rent model,' in which manufacturers retain ownership of products and simply rent them to customers."

These paragraphs add a property, strategy, and a dimension, material recycling to product reuse, to the reuse concept. Descriptions of product recovery and types of recycling infrastructure indicate the presence and importance of this strategy.

Potential Concepts: network (P: constraints D: ?; P: structure D: linear to cyclic), emissions (P: strategy D: efficiency), hazard avoidance (P: strategy D: substitution), reuse (P: strategy D: material recycling to product reuse)

Table 258: Summary of potential concepts, properties and dimensions for U.S. Congress 1992 #2

Concepts	Properties	Dimensions
Network	Constraints	?
	Structure	Linear to cyclic
Emissions	Strategy	Efficiency
Hazard avoidance	Strategy	Substitution
Reuse	Strategy	Material recycling to product reuse

Coder	John Reap	Date	10/26/2008
Text Segment	Page 36, Para. 1	Type	Memo
Reference	U.S. Congress, Office of Technology Assessment, *Green Products by Design: Choices for a Cleaner Environment, OTA-E541* (Washington, DC: U.S. Government Printing Office, October 1992): 35-43.		

"…health and environmental laws…influence…costs of releasing wastes…control the use of hazardous chemicals and pesticides directly..."

Early in the chapter, one sees the importance of emissions control and hazard avoidance. The authors reveal these concepts by citing laws dealing with them.

Potential Concepts: emission control, hazard avoidance

Text Segment	Page 37-end	Type	Memo

"Design for waste prevention avoids the generation of waste…design for better material management facilitates the handling of products at the end of service life."

Beginning on page 37, a number of previously noted EBDM concepts appear. The authors list the concepts of resource consumption and reuse in addition to reiterating previously stated concepts. The strategy property appears alongside these concepts. Waste reduction and toxic material reduction are strategies for emissions control and hazard reduction, respectively. Both are evident in their strategic framework and a battery redesign example. Efficiency and life extension are two dimensions of the strategy property for resource consumption. The authors also take care to note that resources have the property of type which varies dimensionally by material or energy. Reuse strategies are present in their framework and in an example of building construction and consumer product (copying machine) remanufacture. These strategies vary from <u>material recycling to remanufacture</u> and include <u>composting</u> and <u>energy recovery</u>.

Potential Concepts: emission control (P: strategy D: waste reduction), hazard avoidance (P: strategy D: toxic material reduction), resource consumption (P: strategy D: efficiency, life extension; P: type D: material or energy), reuse (P: strategy D: material recycling to remanufacture, composting, energy recovery)

Table 259: Summary of potential concepts, properties and dimensions for U.S. Congress 1992 #3

Concepts	Properties	Dimensions
Emissions	Strategy	Waste reduction
Hazard avoidance	Strategy	Toxic material reduction
Resource consumption	Strategy	Efficiency
		Life extension
	Type	Material or energy
Reuse	Strategy	Material recycling to remanufacture
		Composting
		Energy recovery

Coder	John Reap	Date	8/22/2008
Text Segment	Abstract to para. 3	Type	Memo
Reference	Vanegas, J.A. (2003). Road Map and Principles for Built Environment Sustainability. *Environmental Science & Technology* 37: 5363-5372.		

"…people and organizations around the world has been promoting the concept of sustainable development..."

The sustainable development concept provides the overarching frame in which Vanegas presents his ideas. Properties such as time and degree further specify this framework. Time varies from the current generation to future generations while degree varies form unsustainable to sustainable.

Potential concepts: sustainable development (P: time D: current to future generations; P: degree D: unsustainable to sustainable)

Text Segment	Para. 4 - 15	Type	Memo

"…owners are paying more attention in their projects to the optimization of resource use, reduction or elimination of waste, enhancement of environmental compatibility, and satisfaction of intra- and inter-generational needs..."

The author states guidance that might move systems toward sustainability. The quoted passage shows that he associates concepts such as resource reduction and environmental compatibility with sustainable development. Strategies for achieving resource reduction include waste elimination and efficiency. Properties and dimensions that better define the environmental compatibility concept are not presented in this section.

Potential concepts: sustainable development (P: time D: current to future generations; P: degree D: unsustainable to sustainable), resource reduction (P: strategy D: waste elimination, efficiency), environmental compatibility

Text Segment	Para. 16-end	Type	Memo

"This system contains several characteristics that are key to achieving sustainability…"

At various points in the remainder of the article, the author states ideas meant to promote or deemed necessary for sustainability. Hazard avoidance, a concept commonly found in EBDM literature, is clearly present in the form of the strategy of substitution. Reuse is also present, and the author states strategies ranging from product reuse to recycling.

A property of environmental compatibility also appears in this section. The author presents the idea of resource rate which varies from renewable to depleting. This property helps one understand that environmental compatibility is partially a matter of the speed at which the biosphere generates materials and assimilates wastes.

Potential concepts: sustainable development (P: time D: current to future generations; P: degree D: unsustainable to sustainable), resource reduction (P: strategy D: waste elimination, efficiency), environmental compatibility, Hazard avoidance (P: strategy D: substitution), reuse (P: strategy D: product reuse to recycling)

Table 260: Summary of potential concepts, properties and dimensions for U.S. Congress 1992 #4

Concepts	Properties	Dimensions
Sustainable development	Time	Current to future generations
	Degree	Unsustainable to sustainable
Resource reduction	Strategy	Waste elimination
Environmental compatibility	Resource rate	Renewable to depleting
Hazard avoidance	Strategy	Substitution
Reuse	Strategy	Product reuse to recycling

Coder	John Reap	Date	12/9/2008
Text Segment	Article	Type	Memo
Reference	Veleva, V., M. Hart, T. Greiner and C. Crumbley (2001). "Indicators of sustainable production." *Journal of Cleaner Production* 9(5): 447-452.		

Commonly encountered concepts appear throughout this paper, but the Lowell Center's principles for Sustainable Production encapsulate the guidance offered by the authors. Their statement of principles touches on the concepts of hazard reduction, reuse, resource reduction, bio-compatibility, renewable resources and emission reduction. Concepts such as life cycle and sustainability receive passing mention.

Properties and dimensions for each concept are present in the list of principles or the body of the article. Hazard reduction has the property of type which has dimensions of chemical, ergonomic and physical. It also has the property of strategy which is accompanied by the dimension of elimination in this paper. Reuse strategies vary from recycling to composting. Resource reduction has the properties of type and strategy which are respectively dimensioned by energy or material and efficiency. One might also add durability as a strategy for reducing resource consumption. The only strategy mentioned for bio-compatibility is biodegradability.

Table 261: Summary of potential concepts, properties and dimensions for Veleva 2001

Concepts	Properties	Dimensions
Hazard reduction	Strategy	Elimination
	Type	Chemical, ergonomic and physical
Resource reduction	Strategy	Efficiency
		Durability
	Type	Material or energy
Renewable resources	?	?
Emissions reduction	?	?
Reuse	Strategy	Recycling to composting
Bio-compatibility	Strategy	Biodegradable
Life cycle	?	?
Sustainability	?	?

Coder	John Reap	Date	7/28/2008
Text Segment	Article	Type	Memo
Reference	Vieira, P. S. and A. Horvath (2008). "Assessing the End-of-Life Impacts of Buildings." *Environ. Sci. Technol.* 42(13): 4663-4669.		

"Increasing the recycling of concrete from deconstructed buildings from…27%...to 50% could yield a 2-3%...reduction in buildings' greenhouse gas emissions..."

The authors provide an overview of a modified life cycle assessment method and apply it to end of life assessment for buildings. Concepts relating to guidance for EBDM include life cycle and reuse. Life cycle's property of phase appears in the article, and it varies dimensionally from cradle to grave. Reuse has the property of strategy which only seems to have the dimension of recycling in this paper.

One can identify many other concepts that relate to life cycle assessment's methodology, but since this coding exercise's objective is to focus on those related to guiding principles, such concepts are not presented.

Potential Concepts: reuse (P: strategy D: recycling), life cycle (P: phase D: cradle to grave)

Table 262: Summary of potential concepts, properties and dimensions for Vieira 2008

Concepts	Properties	Dimensions
Reuse	Strategy	Recycling
Life cycle	Phase	Cradle to grave

Coder	John Reap	Date	11/16/2008
Text Segment	Article	Type	Memo
Reference	Waage, S. A. (2007). "Re-considering product design: a practical "road-map" for integration of sustainability issues." *Journal of Cleaner Production* 15(7): 638-649.		

Since the author intended to create a "roadmap" for sustainable product design, he largely discusses how one might use sustainability principles and assessment tools. He does not provide many principles or guidelines, however. He only presents guidelines on one page. They cover the concepts of <u>resource consumption reduction</u>, <u>emissions reduction</u>, <u>hazard avoidance</u> and <u>biological integrity</u>. <u>Strategies</u> for reducing resource consumption and avoiding hazards include <u>efficiency</u>, <u>renewables</u> and <u>substitution</u>, respectively.

Potential Concepts: emissions, biological integrity, resource consumption (P: strategy D: efficiency, renewables), hazard avoidance (P: strategy D: substitution)

Table 263: Summary of potential concepts, properties and dimensions for Waage 2007

Concepts	Properties	Dimensions
Biological integrity	?	?
Resource consumption	Strategy	Efficiency
		Renewables
Emissions	?	?
Hazard avoidance	Strategy	Substitution

Coder	John Reap	Date	7/27/2008
Text Segment	Abstract – Paragraph 3	Type	Memo
Reference	Lee, B.H. and K. Ishii (1997) "Demanufacturing Complexity Metrics in Design for Recyclability" *IEEE: 0-7803-3808-1*.		

"…illustrate the difference between a priori and contingent approaches to product design..."

The relationship between the two concepts of design and sustainability play a central role in this paper. The author sees two approaches to design – a priori or contingent. Later in this coded section, the author's preference for a contingent approach to design becomes clear.

Potential Concepts: design (P: approach D: a priori to contingent)

Text Segment	Paragraph 13-end	Type	Memo

"…consumption patterns are, in very many ways, often physically, ethically and spiritually unsustainable."

Sustainability's traditional properties emerge in these paragraphs. Social, economic and environmental sustainability are vague but present. Social sustainability seems to vary dimensionally from unfulfilled to flourishing while economic sustainability varies from chaotic to stable. The environment is seen as varying from degraded to healthy.

Potential Concepts: design (P: approach D: a priori to contingent), sustainability (P: social D: unfulfilled to flourishing; P: economic D: chaotic to stable; P: environment D: degraded to healthy)

Table 264: Summary of potential concepts, properties and dimensions for Lee 1997

Concepts	Properties	Dimensions
Design	Approach	A priori to contingent
Sustainability	Social	Unfulfilled to flourishing
	Economic	Chaotic to stable
	Environmental	Degraded to healthy

Coder	John Reap	Date	9/8/2008
Text Segment	Article	Type	Memo
Reference	Wallner, Heinz P. (1999) "Towards sustainable development of industry: networking, complexity and eco-clusters" *Journal of Cleaner Production* 7: 49-58.		

"The most critical innovation of the industrial ecology concept is the level of inter-enterprise co-operation."

This statement and a number of others like it place networks and networking at the heart of this paper. Networking is in the title and is often placed alongside other concepts such as sustainable development and carrying capacity in the abstract and introductory paragraphs. The authors clearly believe that changes in industrial, economic and even social networks are needed to achieve sustainability.

They devote much of the text to defining the types of networks envisioned. These discussions provide numerous properties: complexity, energy source, type and temporal development. Complexity varies by entity number, diversity, interaction number and interaction intensity. Energy source is either renewable or depleting. Temporal development varies dimensionally from early to late. Network type varies by actor (different industries) and by exchange variable (information, energy, material).

Potential Concepts: networks (P: complexity D: entity number, diversity, interaction number, interaction intensity; P: energy source D: renewable or depleting; P: type D: actor, exchange variable; P: temporal development D: early to late), sustainable development, carrying capacity

Table 265: Summary of potential concepts, properties and dimensions for Wallner 1999

Concepts	Properties	Dimensions
Networks	Complexity	Entity number
		Diversity
		Interaction number
		Interaction intensity
	Energy source	Renewable or depleting
	Type	Actor
		Exchange variable
	Temporal development	Early to late
Sustainable development	?	?
Carrying capacity	?	?

Coder	John Reap	Date	10/22/2008
Text Segment	Article	Type	Memo
Reference	Xing, K. and M. Belusko (2008). "Design for Upgradability Algorithm: Configuring Durable Products for Competitive Reutilization". *Journal of Mechanical Design* 130: 1-14.		

This article describes a design for upgradability (DFU) method. Most of the article details the construction and application of this method, but one can find a few parts that mention environmental factors. One table summarizes these factors as constraints on energy consumption and materials. One can further partition the material constraint into constraints on total material used, toxicity and compatibility with recycling processes. The presence of these constraints reveals that the authors are concerned with the concepts of <u>resource consumption</u>, <u>emission reduction</u>, <u>reuse</u> and <u>hazard avoidance</u>.

Constraints on energy and materials show that resource consumption has the property of <u>type</u> which varies discretely as <u>energy or material</u>. Properties and dimensions for the other concepts briefly alluded to in this article are not clearly defined.

Potential Concept: emission reduction, reuse, hazard avoidance, resource consumption (P: type D: energy or material)

Table 266: Summary of potential concepts, properties and dimensions for Xing 2008

Concepts	Properties	Dimensions
Emission reduction	?	?
Reuse	?	?
Hazard reduction	?	?
Resource consumption	Type	Energy or material

Coder	John Reap	Date	12/20/2008
Text Segment	Abstract	Type	Memo
Reference	York, Richard E. A. R. T. D. (2004). "The Ecological Footprint Intensity of National Economies." *Journal of Industrial Ecology* 8(4): 139-154.		

"…EF of a nation is the amount of land area that would be required to produce the resources it consumes and to absorb the wastes it generates."

The abstract contains the primary concepts discussed in the article. The body of the article is devoted to an application of them. The included citation indicates that the authors focus on <u>resource consumption</u> and <u>emissions</u>. Both have the property of <u>level</u> or degree that one can dimension using <u>land area</u>.

Potential Concepts: resource consumption (P: level D: land area), emissions (P: level D: land area)

Table 267: Summary of potential concepts, properties and dimensions for York 2004

Concepts	Properties	Dimensions
Resource consumption	Level	Land area
Emissions	Level	Land area

Coder	John Reap	Date	7/15/2008
Text Segment	Article	Type	Memo
Reference	Zhang, H-C., S.Y. Yu (1997) "An Environmentally Conscious Evaluation / Design Support Tool for Personal Computers". *Proceedings of the 1997 5th IEEE International Symposium on Electronics and the Environment, ISEE*. May 5-7, San Francisco, USA.		

"Design for Environment (DFE)…comprises several design-related issues…disassembly, recyclability, health influence, safety impact, and hazard material minimization etc.)

One finds this article's concepts on the first page. The concepts of reuse and hazard avoidance take the form of health, hazardous materials, disassembly and recycling concerns. Strategies for dealing with these concerns include material recycling to product reuse and toxic material minimization, respectively. On pages 133-134, the authors add more dimensional richness to the reuse strategy by mentioning incineration and down cycling as reuse strategies.

Potential Concepts: reuse (P: strategy D: material recycling to product reuse, down cycling, incineration), hazard avoidance (P: strategy D: toxic material minimization)

Table 268: Summary of potential concepts, properties and dimensions for Zhang 1997

Concepts	Properties	Dimensions
Hazards avoidance	Strategy	Toxic material minimization
Reuse	Strategy	Material recycling to product reuse
		Down cycling
		Incineration

Coder	John Reap	Date	9/2/2008
Text Segment	Article	Type	Memo
Reference	Zvolinschi, A., S. Kjelstrup, O. Bolland and H.J. van der Kooi (2007). "Exergy Sustainability Indicators as a Tool in Industrial Ecology" *Journal of Industrial Ecology* 11(4): 85-98.		

"…importance of understanding the quality of energy needs in industrial systems, and...the need to discuss where and how the energy quality or exergy degrades…"

Life cycle, sustainability and resource consumption reduction concepts appear in this paper, but the primary focus is on energy resources. Within the context of resource reduction, the authors discuss the strategy of efficiency.

Differentiating the concept of consumption reduction from the simple concept of resources is appropriate in this article. Resources clearly vary by type between material or energy. The quote indicates that the resource concept has the property of quality which varies from low to high. One may also assign the renewable property to resources; it also varies from low to high and by exergy renewability.

Potential Concepts: life cycle, sustainability, resource consumption reduction (P: strategy D: efficiency), resources (P: type D: material or energy; P: quality D: low to high; P: renewable D: low to high, D: exergy renewability)

Table 269: Summary of potential concepts, properties and dimensions for Zvolinschi 2007

Concepts	Properties	Dimensions
Resources	Type	Material or energy
	Quality	Low to high
	Renewable	Low to high
		Exergy renewability
Life cycle	?	?
Sustainability	?	?
Resource consumption reduction	Strategy	Efficiency

APPENDIX F

INDUSTRIAL SYMBIOSIS INFORMATION

This appendix contains descriptions, diagrams and tables for 29 industrial symbioses. One should note that some diagrams contain information for more than one version of a symbiosis.

1. AES Montville EIP

A craft brewery forms the core of the proposed eco-industrial park for Montville, Connecticut (Becker, et al. 2002). It receives and outputs multiple waste streams. The Brewery's existence motivates the four major types of diagramed flows: material for soil, thermal energy, farm products and packaging materials. In conjunction with the farms, it structurally closes the eco-park's waste material and energy loops.

Only two business pictured in Figure 80 were absent at the time of the proposal's creation. However, many of the links did not exist, and the critically important brewery and farm were the missing businesses. AES Montville EIP is, therefore, only a proposal.

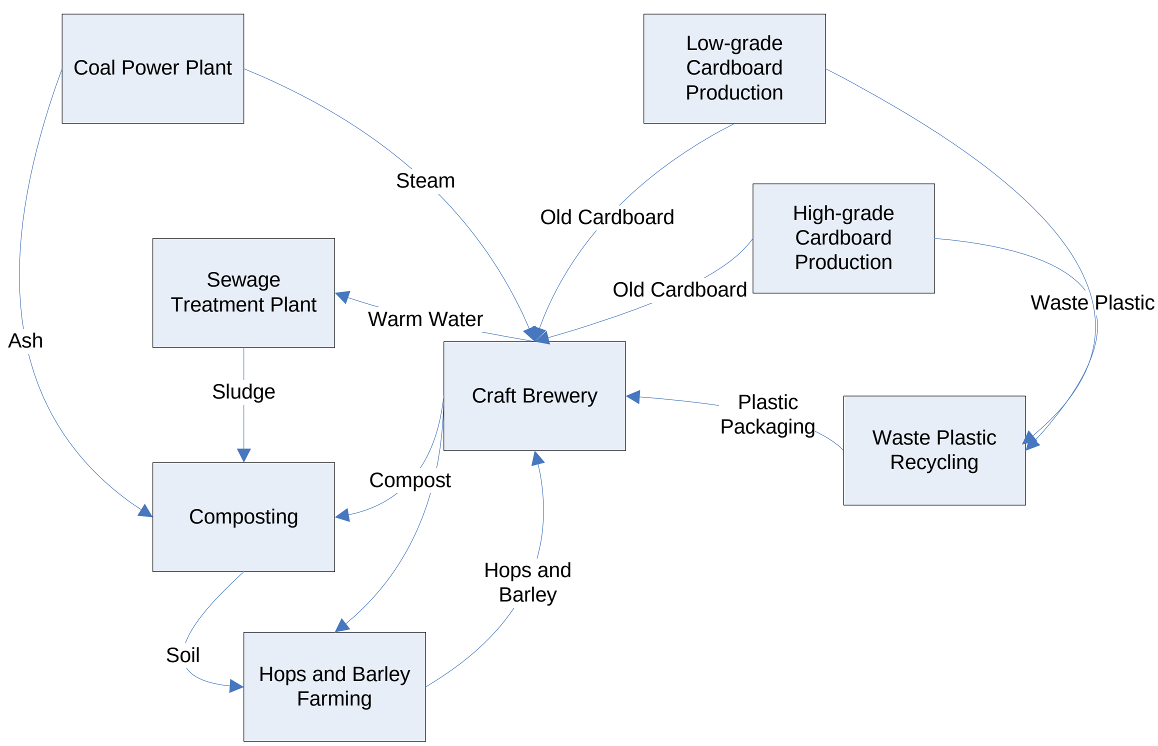


Figure 80: AES Montville EIP - Craft Brewery Proposal

2. An Son Village

An Son is a proposed integrated biosystem formed from a simple waste cascade. Based on common activities and products found in Vietnamese villages, the An Son model uses a biodigestor to transform effluent from pig husbandry into nutritive fertilizer for traditional crops such as rice, sugarcane and pak choi (Hardy 2001).

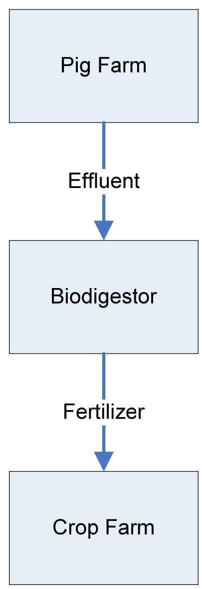


Figure 81: An Son Village

3. Clark Special Economic Zone

The Clark Special Economic Zone in the Philippines contains multiple industries producing a number of wastes that one might put to better use. The proposal by Bennett and coauthors describes one possible configuration for an eco-park at the Clark site (Bennett, et al. 2002). Their proposal contains provisions for solvent recovery, oil processing, tire processing, gray water treatment, composting and better integration of a power plant. Table 270 lists the main flows linking the proposed components of the eco-park. Given the complexity of the interactions, a table is used to describe the eco-park's structure (See Table 271).

One should keep two important points in mind when reviewing the following tables. First, Table 271 represents a summation of the major reuse subsystems described by Bennett, not the diagram found at the close of their report. Second, the solvent, oil, tire, water and organic material major recyclers are hypothetical, and the authors of the Clark report emphasize that it is a proposal, though one made in consultation with those overseeing the Clark Zone.

Table 270: Reusable inputs and outputs for listed businesses

#	Activity	Emits	Receives
1	Airport	Used oil, used tires	
2	Alternative Fuels		Reprocessed solvents
3	Composting	Compost	Organic matter
4	Electronics	Waste water, used solvents	Water
5	Golf Course	Organic matter	Water, compost, shredded tires
6	Greenhouses	Organic matter	Compost
7	Grey Water Processing	Water	Waste water
8	Housing	Waste water, used oil, used tires	Water, reprocessed oil
9	Landscaping	Organic matter	Water, compost
10	Metal Fabrication	Used solvents	Used solvents, reprocessed solvents
11	Oil Processing	Reprocessed oil	Used oil
12	Old Power Plant		Shredded tires
13	Plastics	Used oil, used solvents	Reprocessed oil, used solvents
14	Power Plant	Waste water, used solvents, steam	Water, used solvents
15	Solvent Recovery	Reprocessed solvents	Used solvents
16	Textiles	Waste water, used solvents	Water, used solvents
17	Tire Manufac.	Waste water, used oil, used solvents, off spec. tires	Water, reprocessed oil, used solvents
18	Tire Processing	Shredded tires	Used tires, off-spec. tires
19	Tobacco	Organic matter	
20	Cosmetics		Steam

Table 271: Connections between businesses / activities in the Clark Zone

		From Process #																			
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
To Process #	1																				
	2															x					
	3					x	x			x										x	
	4							x													
	5			x				x											x		
	6			x											x						
	7				x				x						x		x	x			
	8							x				x									
	9			x				x													
	10				x											x					
	11	x							x					x				x			
	12																		x		
	13				x							x				x					
	14				x			x								x					
	15										x			x	x		x	x			
	16				x			x								x					
	17				x			x				x			x	x					
	18	x							x									x			
	19														x						
	20														x						

4. Connecticut Newsprint

A proposed eco-industrial park built around recycled newsprint.

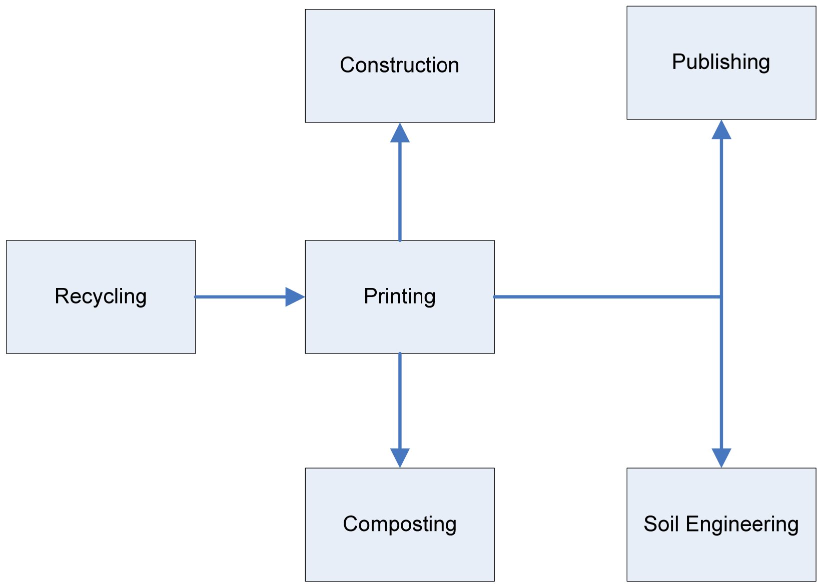


Figure 82: Connecticut Newsprint

5. Devons EIP

A proposed eco-industrial park meant to recover and recycle: solvents, plastics, cardboard and biodegradable organic materials.

Table 272: Businesses in the Devons EIP

#	Business
1	Municipal waste
2	Cain's Foods
3	Parm-Eco
4	Nestal
5	Electronics
6	Plastic Recycle
7	Southern Container
8	Solvent Recycle
9	Composting
10	Parker-Hannifin
11	Ryerson Tull
12	Sunoco Products
13	Comoco Graphics
14	Elora Software
15	Image Software
16	Webvan
17	Loaves and Fishes
18	Golf Course
19	Landscaping
20	Greenways
21	Markson-Rosenthal

Table 273: Connections between businesses in Devons symbiosis

		To Business #																				
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
From Business #	1						x															
	2									x												
	3								x													
	4							x														
	5								x													
	6												x	x	x	x						
	7										x		x			x						x
	8																					
	9																		x	x	x	
	10								x			x										
	11							x	x		x											
	12							x														
	13																					
	14																					
	15							x														
	16							x		x												
	17							x		x												
	18									x												
	19									x												
	20									x												
	21																					

6. Fushan Farms (IBS)

The integrated bio-system at Fushan farms collects, converts and reuses or sells farm wastes (Chengchun 2001). The major components of the IBS are a chicken farm, a pig farm and biogas production units. These three activities and a few ancillary processes form a simple agricultural resource cascade diagramed in Figure 83. Biogas used in chicken farming to heat chicken coops and incubate eggs creates the only loop in the system.

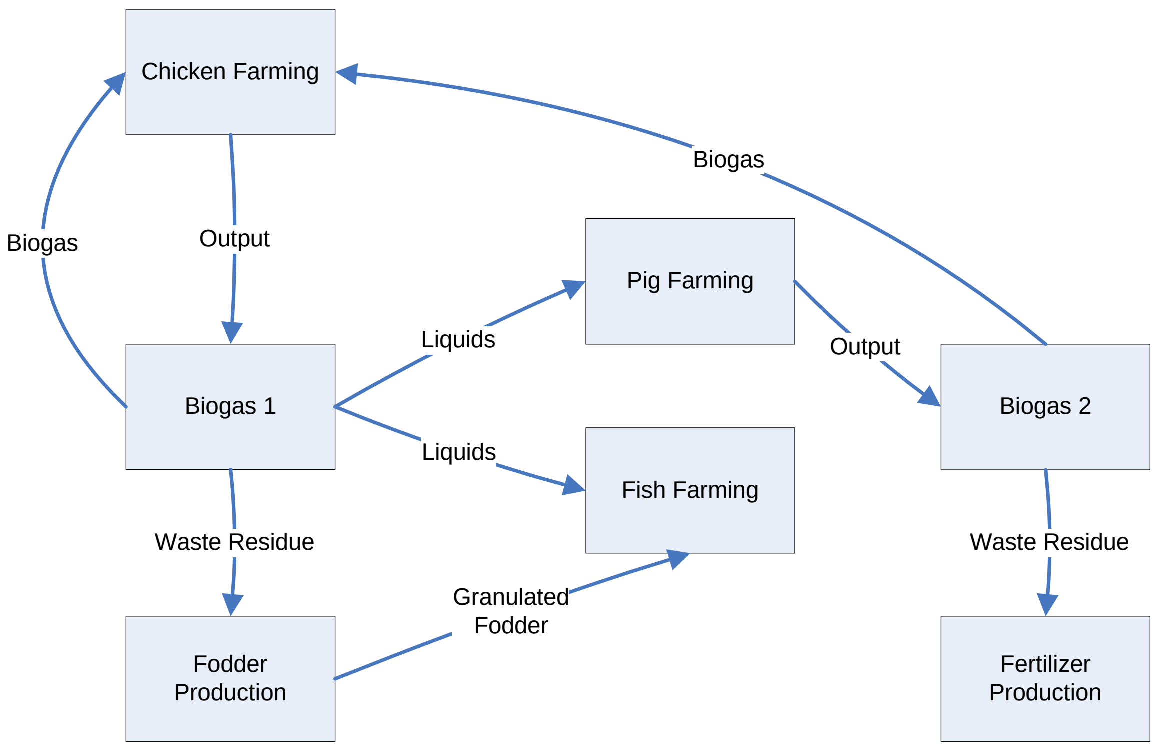


Figure 83: Fushan Farms integrated bio-system

7. GERIPA (IBS)

The proposed GERIPA (Geracao de Energia Renovavel Integrada a Producao de Alimentos) system is an alternative to traditional alcohol and sugar production from sugarcane (Ometto, et al. 2007). It blurs the distinction between industrial eco-parks and integrated bio-systems by containing common elements of both. It depends on sugarcane farming and includes ranching, but it also integrates a cogeneration power plant. Material flows diagramed in Fig. begin in the sugarcane fields. Sugarcane and harvest residues supply an alcohol production facility, a power plant and cattle breeding. In addition to saleable electricity, the power plant provides process heat to other parts of the GERIPA. The alcohol production complex's major activities include juice processing, fermentation and distillation. As diagramed by Ometto and coauthors, one recovers yeast from fermentation and prepares it for sale during a separate yeast treatment process (Ometto, et al. 2007). This process provides biogas for the cogeneration plant and fertilizer for the cane fields in addition to producing marketable yeast.

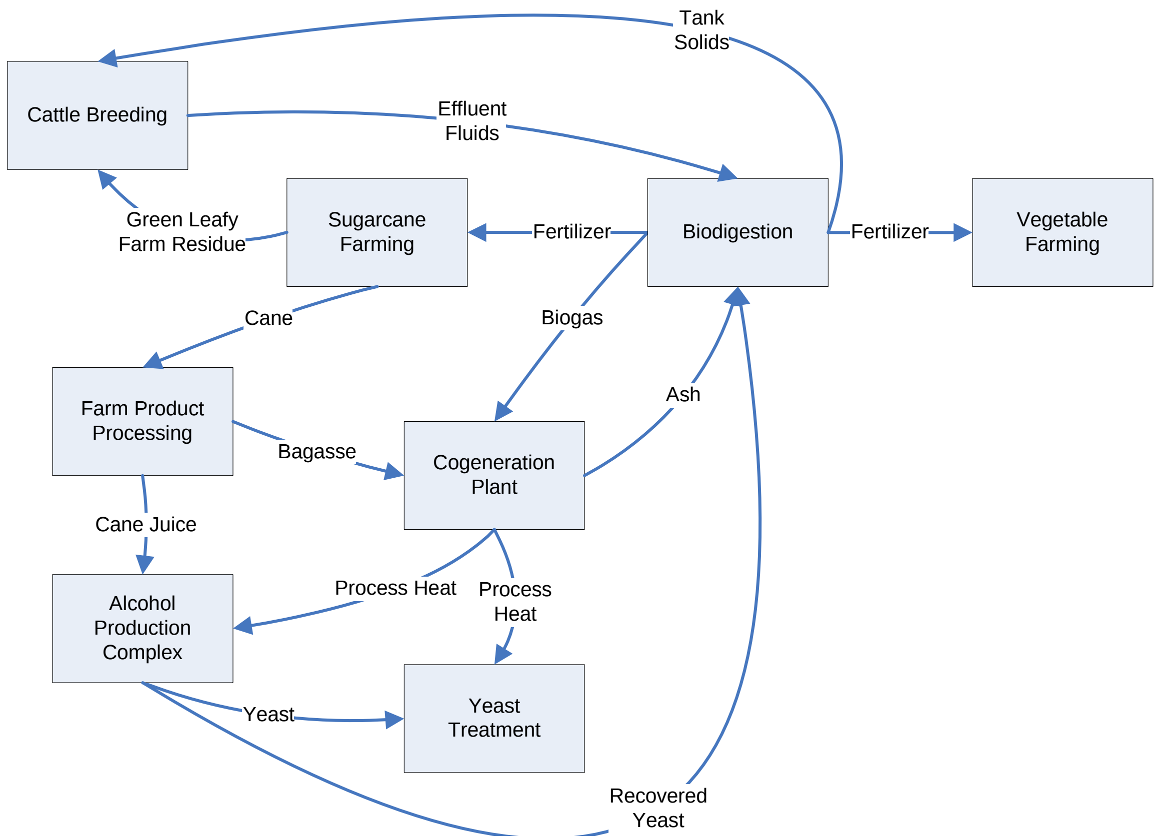


Figure 84: GERIPA system

8. Gladstone

Gladstone, Australia is home to a documented waste and byproduct cascade built around domestic, power production and mineral processing waste streams (van Beers, et al. 2007). All participants fall within roughly 15 km of the town. The cascade connects sewage treatment, tire collection, solvent collection, power generation, cement production and two steps in aluminum production as shown in Figure 85. Key participants in the cascade include the cement producer which incinerates multiple wastes and the aluminum smelter which cut it consumption of scare water resources by using treated sewage effluent from the town of Gladstone.

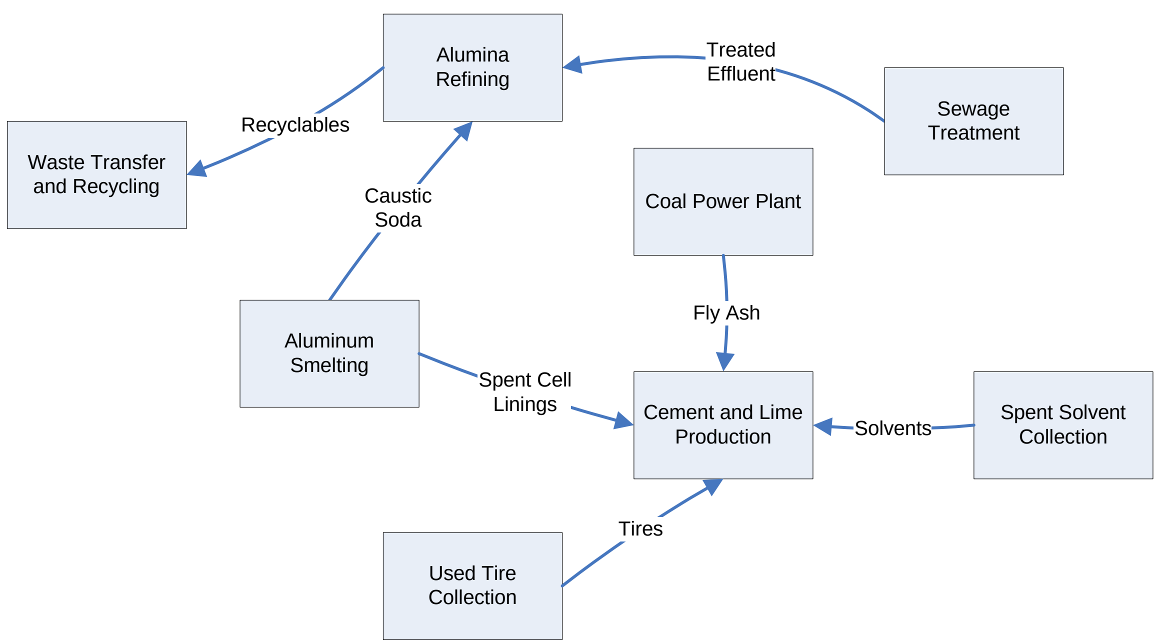


Figure 85: Waste and byproduct cascade in Gladstone

9. Green Triangle

The Green Triangle is a proposed resource exchange between the Franklin Zoo, Arnold Arboretum and other nearby businesses.

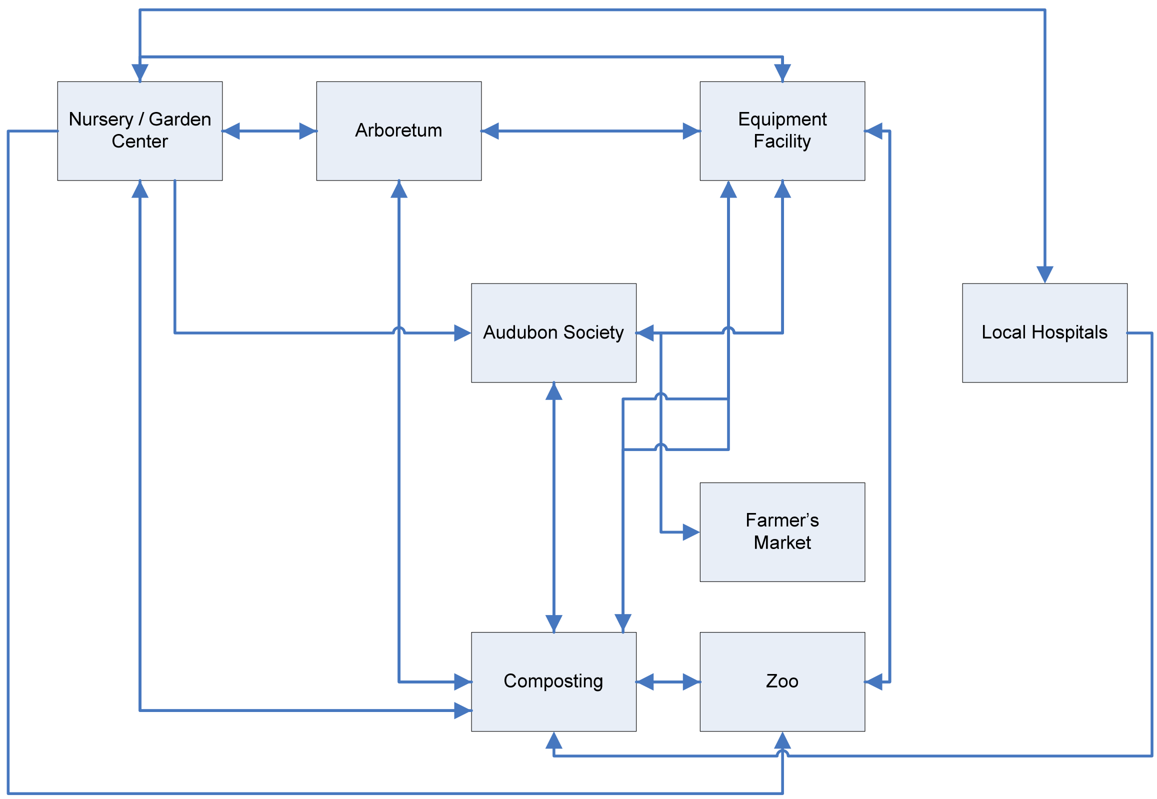


Figure 86: The Green Triangle eco-industrial park

10. Guayama

Guayama, Puerto Rico hosts a recently established resource cascade that links a waste water treatment plant to a petrochemical facility via a power plant (Chertow, et al. 2005a). Chertow and Lombardi estimate that this cascade reduces power plant water consumption by 4 million gallons per day and achieves a percent reduction in some products of combustion approaching 99% (Chertow, et al. 2005a). The region hosts many of the same types of industries found in Kalundborg, Denmark, and therefore, it may hold the potential to develop further connections over time. Figure 87 illustrates the current cascade as well as proposed links to neighboring pharmaceutical plants and soil stabilization activities.

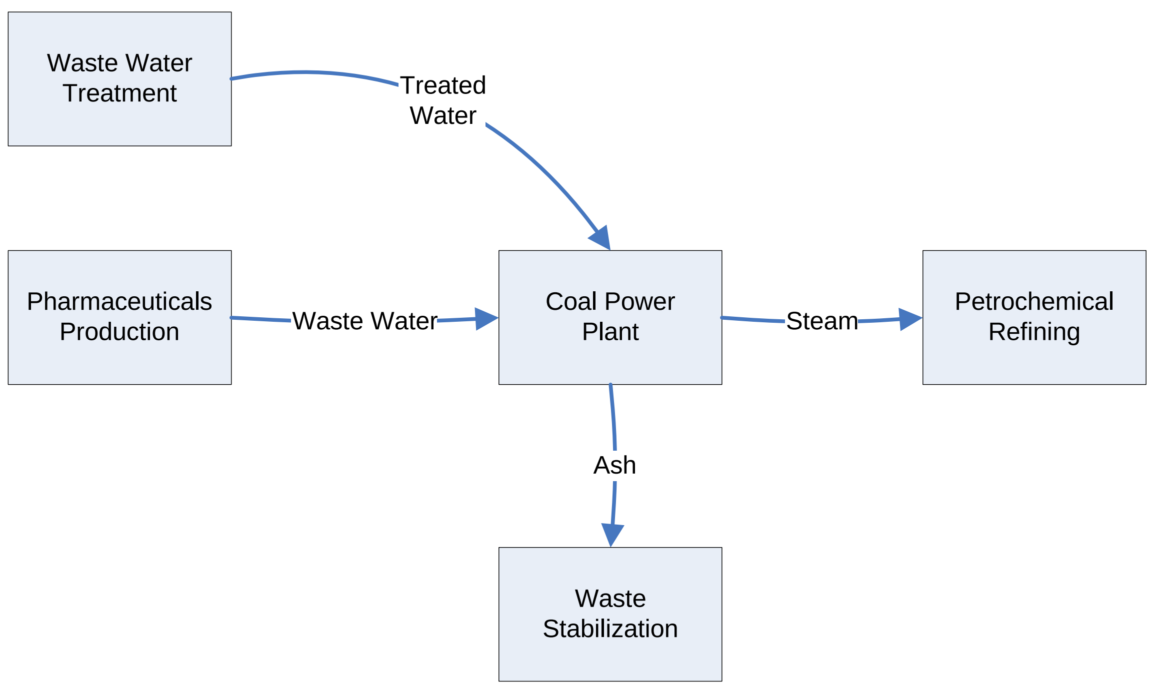


Figure 87: Resource cascade in Guayama, Puerto Rico

11. Guitang Group

The Guitang Group's primary business is sugar production, but over the course of four decades it developed the multi-industry symbiosis pictured in Figure 88 (Zhu, et al. 2007). The symbiosis encompasses alcohol, cement, fertilizer, paper and power production in addition to the core activities of sugarcane farming and sugar refining. Industrial activities occur in a 2 km^2 industrial park while the sugarcane farming occurs in the surrounding Guangxi Zhuang Autonomous Region. Zhu and coauthors believe that the symbiosis improved the Guitang Group's resource and economic efficiency (Zhu, et al. 2004, Zhu, et al. 2007), and consequently, one can reason it avoided environmental burdens that would have resulted from a less efficient system.

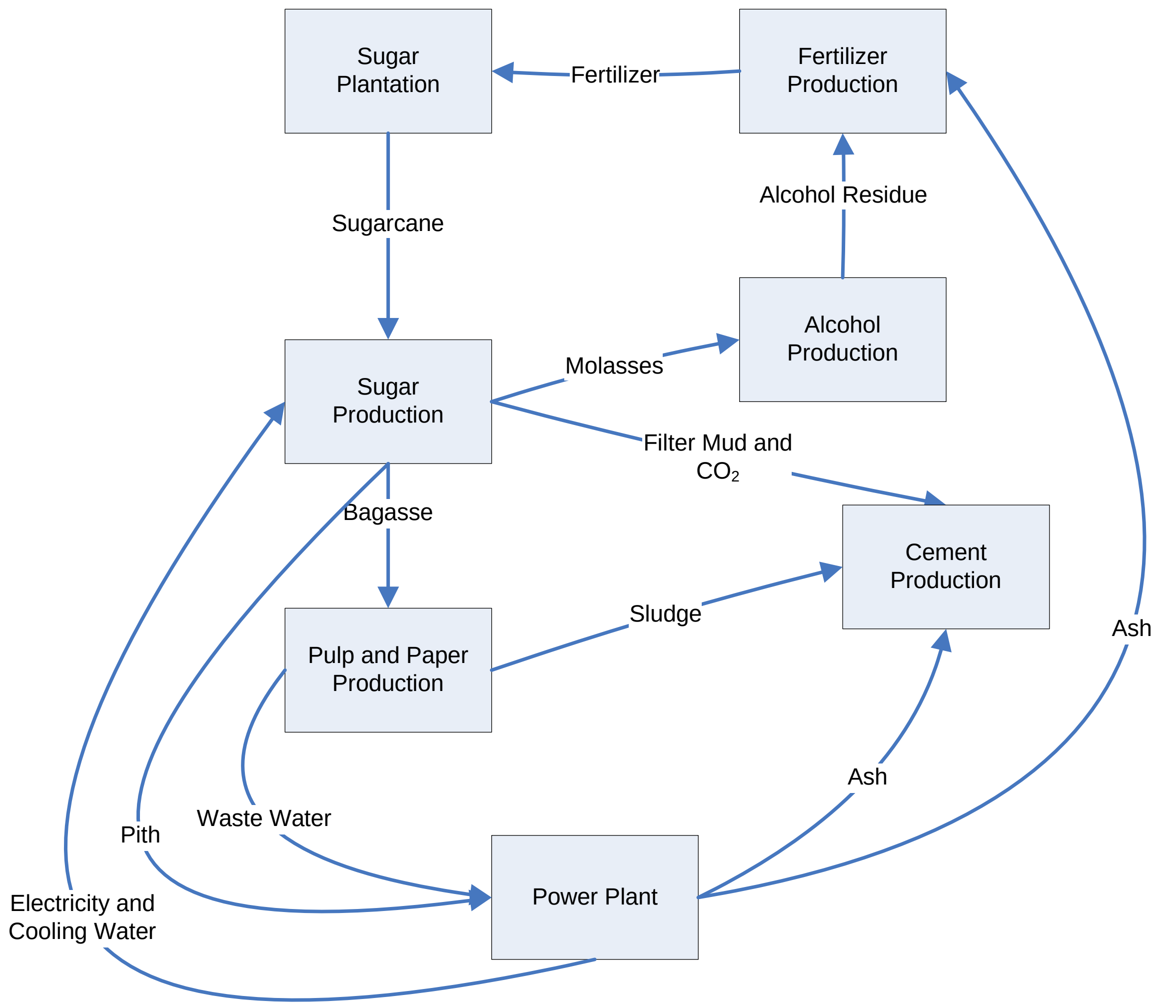


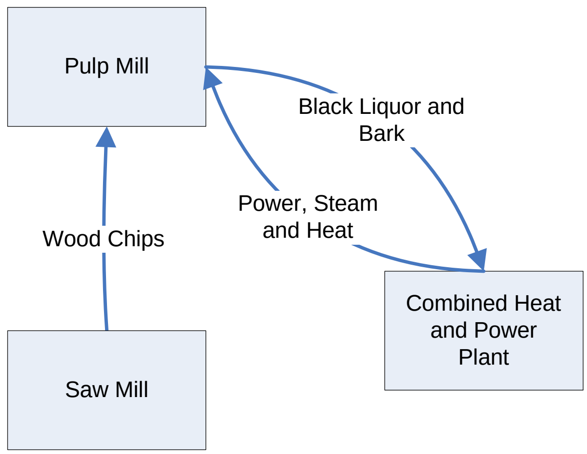
Figure 88: Guitang Group's eco-industrial park

12. Uimaharju

Eastern Finland's Uimaharju eco-industrial park began life as a sawmill in the 1950s. In time, other businesses moved into the region and began using the outputs, byproducts and wastes generated by established activities. Korhonen and Snakin provide the information necessary to construct the physical connections for three periods in the park's development (See Figure 89) (Korhonen, et al. 2005). In the final configuration, a sawmill, pulp mill and a combined heat and power plant form the core of an industrial cluster that also includes waste water treatment, gas recovery and ash treatment.

1955-1966

1967-1992



1992-2003

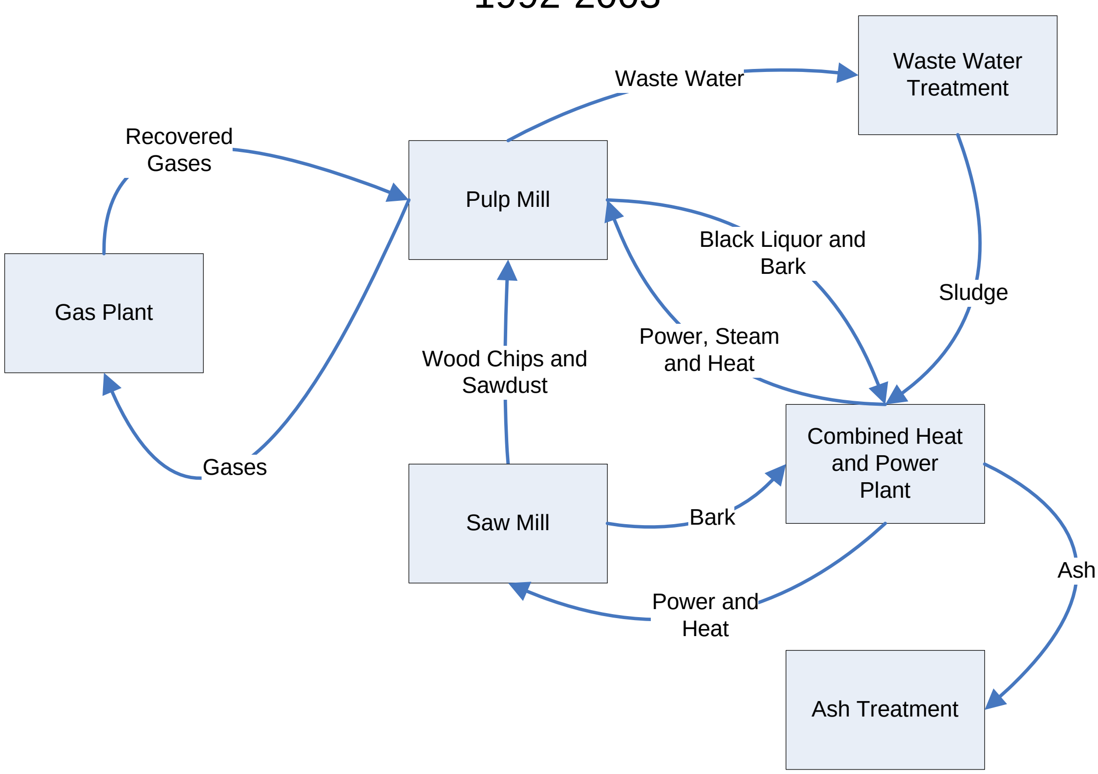


Figure 89: Uimaharju EIP's development

13. Kalundborg

Kalundborg, Denmark is home to an oft cited and studied eco-industrial park (Ehrenfeld, et al. 1997, Jacobsen 2006). A coal-fired power plant rests at the heart of the symbiosis. Waste heat, steam and products of combustion flow from the power plant to many businesses in the surrounding area (See Figure 90). An oil refinery, pharmaceutical plant and wallboard producer are also key players in the material and energy exchange network.

Kalundborg's symbiosis developed over the course of 25 years in response to groundwater constraints and increasing environmental regulations (Ehrenfeld, et al. 1997, Jacobsen 2006). Ehrenfeld and Gertler trace the history of the symbiosis' development while Jacobsen quantifies one of its important flows – water (Ehrenfeld, et al. 1997, Jacobsen 2006).

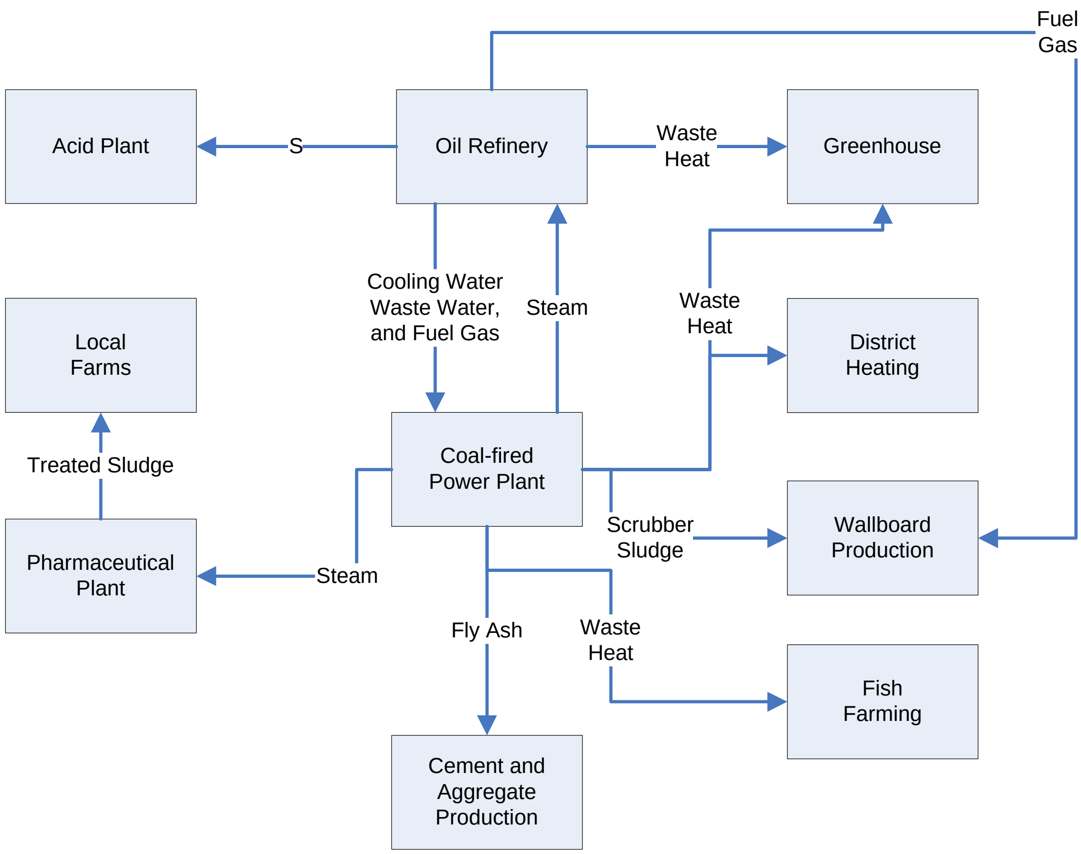


Figure 90: Kalundborg's Industrial Symbiosis

14. Kwinana

Australia hosts a multitude of material and energy exchanges in its Kwinana industrial symbiosis.

Table 274: Outputs / emissions utilized in the Kiwana industrial symbiosis

#	Facility/ Business	Outputs	Inputs
1	Alumina refinery	Domestic organic waste, bauxite residue, electricity	CO_2, gypsum, recycled water
2	Cement and lime production	Lime kiln dust	Spent catalysts, mine overburden
3	Chemical and fertilizer production	CO_2, H_2, gypsum, methyl diethyl amine, bore water, sea water	H_2, $(NH_4)SO_4$, wastewater, demineralized water, sea water, reclaimed water
4	Chemical production	Wastewater	
5	Chlor Alkali Plant	80% H_2SO_4, wastewater	98% H_2SO_4, steam, potable water, electricity
6	Coal mining	Coal mine overburden	
7	Coal-fired power plant	Fly ash, demineralized water	H_2, CO_2, boiler blowdown
8	Co-generation plant (1)	Steam, electricity, wastewater	Fuel gas, reclaimed water
9	Co-generation plant (2)	Wastewater, steam, electricity	Potable water, air, reverse osmosis water
10	Composing facility		Spent CPU catalyst
11	Construction company		Fly ash
12	Fertilizer production		$(NH_4)SO_4$
13	Gas-fired power plant	Boiler blowdown	Demineralized water
14	Industrial gas production (1)	H_2, CO_2	H_2, CO_2, electricity
15	Industrial gas production (2)	H_2, CO_2	Steam, H_2, CO_2
16	Inorganic chemical production	98% H_2SO_4, NH_4Cl	80% H_2SO_4, NH_4Cl solution, S, HCl
17	Nickel mining		Process residue, S
18	Nickel refining	Process residue, S, CO_2, H_2, $(NH_4)SO_4$	H_2, S
19	Oil refining	Spent CPU catalyst, spent catalyst, H_2, S, sea water, wastewater, fuel gas	Methyl diethyl amine, sea water, steam, electricity, wastewater
20	Pig iron production	Steam	Reclaimed water, lime kiln dust
21	Synthetic rutile production		NH_4Cl
22	Titanium dioxide production	HCl, potable water, steam, electricity, air, reverse osmosis water	Wastewater, steam, electricity, bore water, reclaimed water, lime kiln dust
23	Titanium mineral processing		NH_4Cl solution
24	Turf farm		Bio-sludge

Table 274 continued			
25	Water supply / treatment	Bio-sludge, reclaimed water, recycled water	Bauxite residue
26	Worm farm		Domestic organic waste
27	Zirconia powder producer	NH_4Cl solution	

Table 275: Connections between businesses in the Kiwana symbiosis

		From Process #																										
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
To Process #	1			1											1	1										1		
	2						1													1								
	3				1			1											1	1						1		
	4																											
	5																1						1					
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	23																											1
	24																									1		
	25	1																										
	26	1																										
	27																											

15. Landskrona Industrial Symbiosis Program

Sweden's town of Landskrona contains an existing symbiosis targeted for expansion (Mirata, et al. 2005). A district heating system for the local community is the core of the current system (See Figure 91). Together, the district heating system, local community and local waste management activities form a symbiotic loop. Heat passes to the community which provides domestic waste to waste management which in turn transfers combustible plastic pellets to the district heating system. Other industries increase the length of this energy cascade, and if one ignores employee sharing, plans for expansion appear meant to add energy and water utilization cascades. If, however, one groups the two printing businesses as a single activity, one can argue that the printing sector in Landskrona creates a second symbiotic loop.

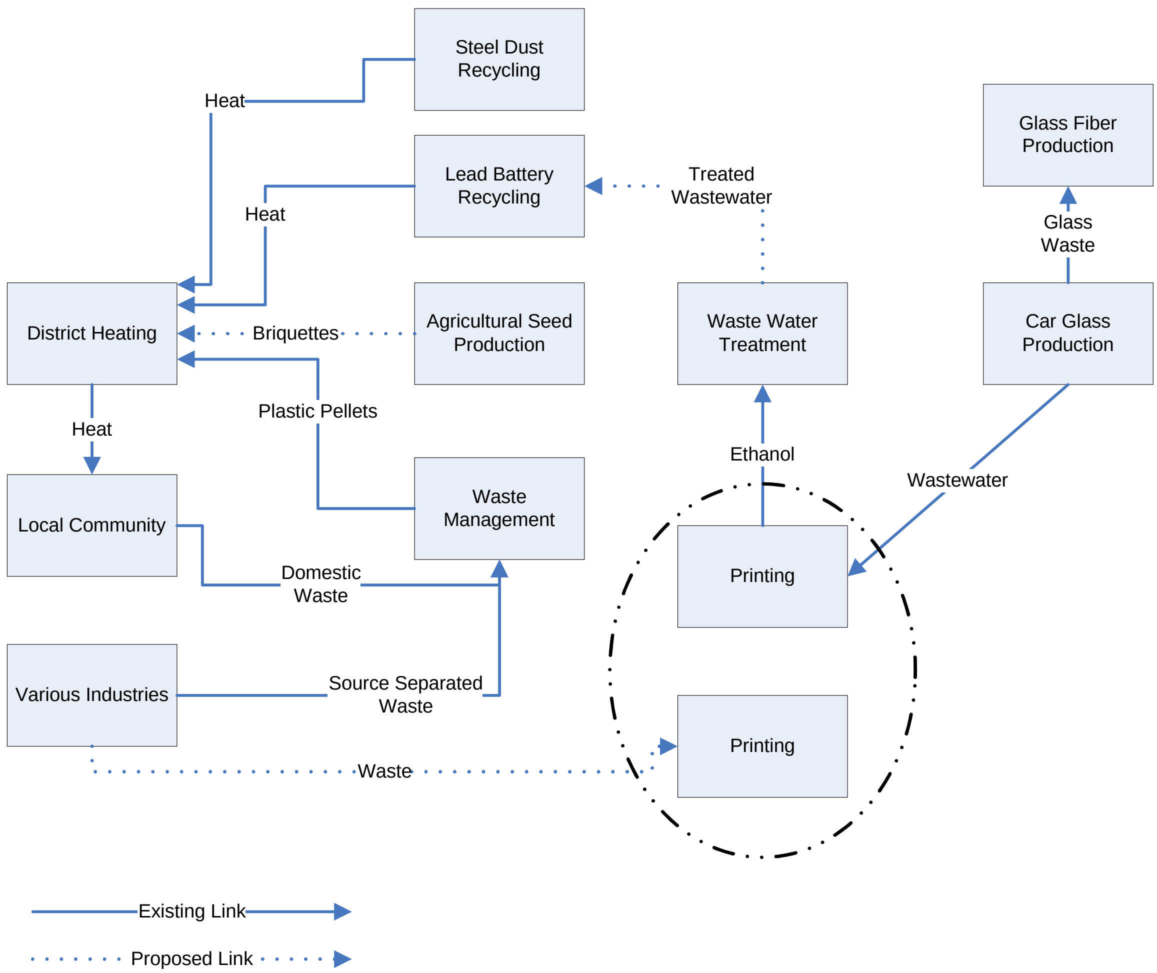

Figure 91: Landskrona Industrial Symbiosis

16. Lower Mississippi Corridor

The following tables contain information about an industrial complex in the Lower Mississippi River Corridor.

Table 276: Activities in the Lower Mississippi River Corridor industrial complex

#	Facility/ Business
1	Ammonia Plant
2	Ammonium nitrate
3	Benefication Plant
4	DME
5	Ethyl-benzene
6	Formic acid
7	Granular triple super phosphate
8	Graphite and Hydrogen
9	Gypsum Production
10	Methanol plant
11	Methylamines
12	Mono and diammonium phosphate
13	New acetic acid
14	New styrene
15	Nitric acid plant
16	Phosphoric acid plant
17	Power generation
18	Propene and hydrogen
19	Propylene plant
20	Sulfuric acid production
21	Syngas
22	UAN plant
23	Urea plant

Table 277: Connections between businesses in the Lower Mississippi Corridor Industrial Complex

		From Process #																						
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
To Process #	1																							
	2															1								
	3																							
	4	1							1										1	1		1		
	5																							
	6	1							1										1	1		1		
	7			1													1							
	8	1																						
	9																1							
	10	1																						
	11	1							1										1	1		1		
	12																1							1
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	19	1																						
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	22		1																					1
	23	1																1			1			

17. Monfort Boys Town Integrated Bio-system

The Monfort school for boys in Suva, Fiji uses waste from a brewery to support multiple agricultural activities and generation of biogas for use in domestic heating or generation of electricity (Chertow 2000). Figure 92 depicts the flow of material and energy carriers through Monfort's integrated bio-system. This system is composed of resource cascades preceding and following a resource exchange loop consisting of pig farming, anaerobic bio-digestion, algae farming and fertilizer production. One should note that this system is on a considerably smaller scale than many other symbioses.

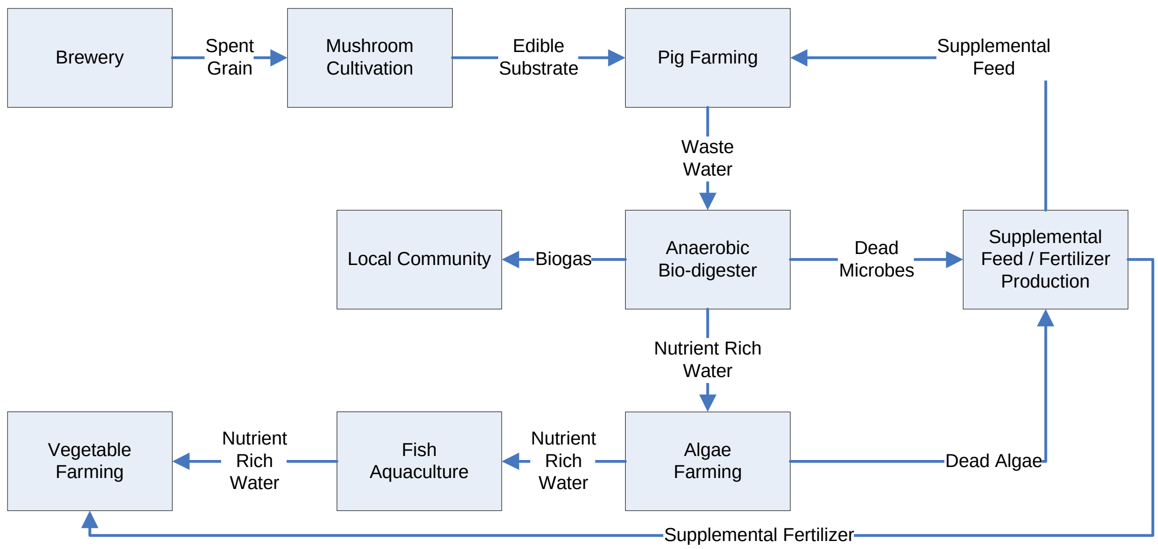

Figure 92: Monfort Boys Town Integrated Bio-System

18. Mongstad EIP

The Mongstad EIP is a proposal to collocate and connect electricity, heat and food producing industries with an existing oil refinery. A combined heat and power (CHP) plant would form the core of the new eco-industrial park. Other notable additions include facilities for carbon dioxide capture, coal gasification and aquaculture.

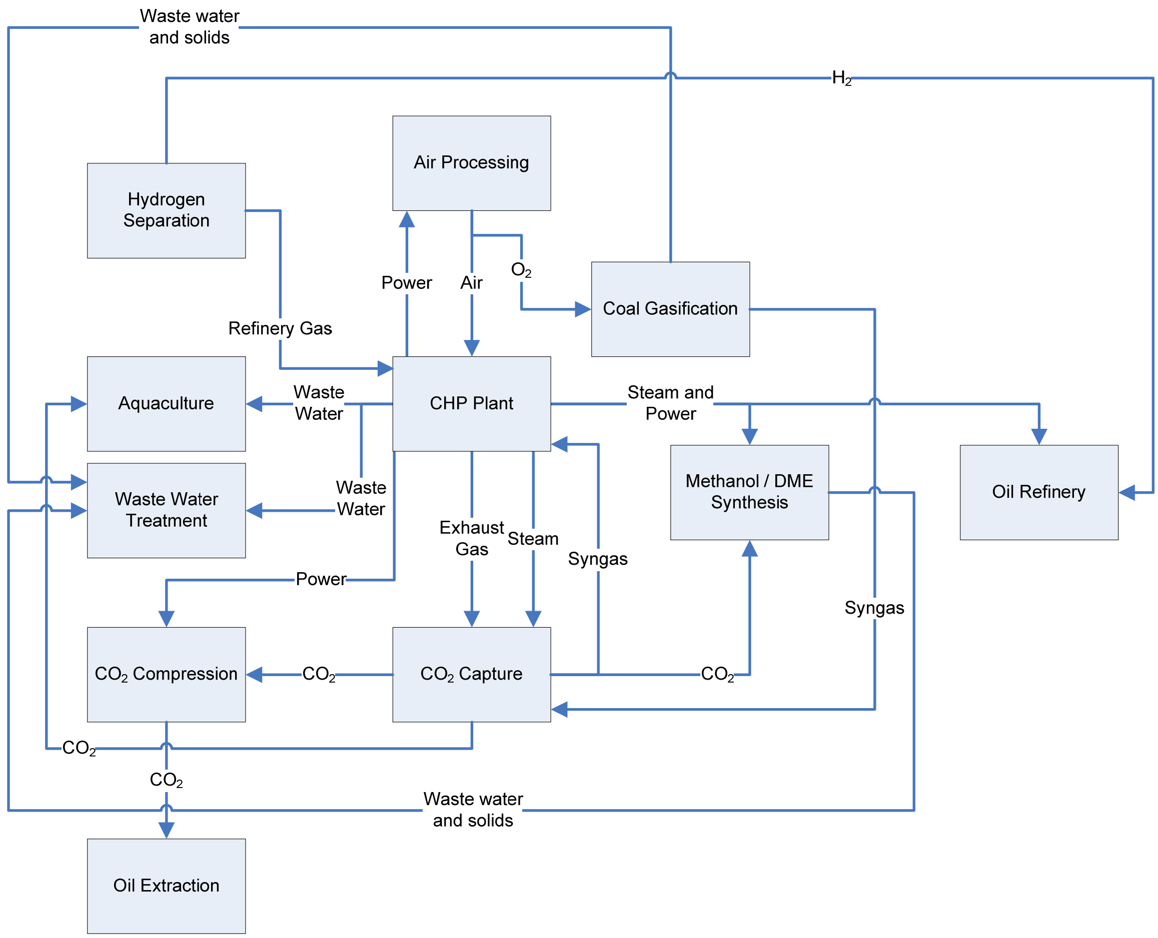

Figure 93: Mongstad EIP

19. Nanning Sugar Company

Six sugar and paper companies merged to form Nanning Sugar Company in response to reduced government protection of the sugar industry in China (Yang, et al. 2008). To improve price competitiveness, production efficiency and environmental profile, the newly formed company sought to better integrate the activities of its newly combined production system. They built the set of symbiotic production activities diagramed in Figure 94.

Figure 94 simplifies the process diagram presented by Yang and Feng (Yang, et al. 2008). Sugar, pulp and paper production incorporate some activities presented as separate in their diagram on the grounds that the incorporated activities would not reasonably operate as independent businesses. Boilers are considered part of the sugar and pulp production process. Alkali recover is grouped with pulp production, and paper production includes white water production.

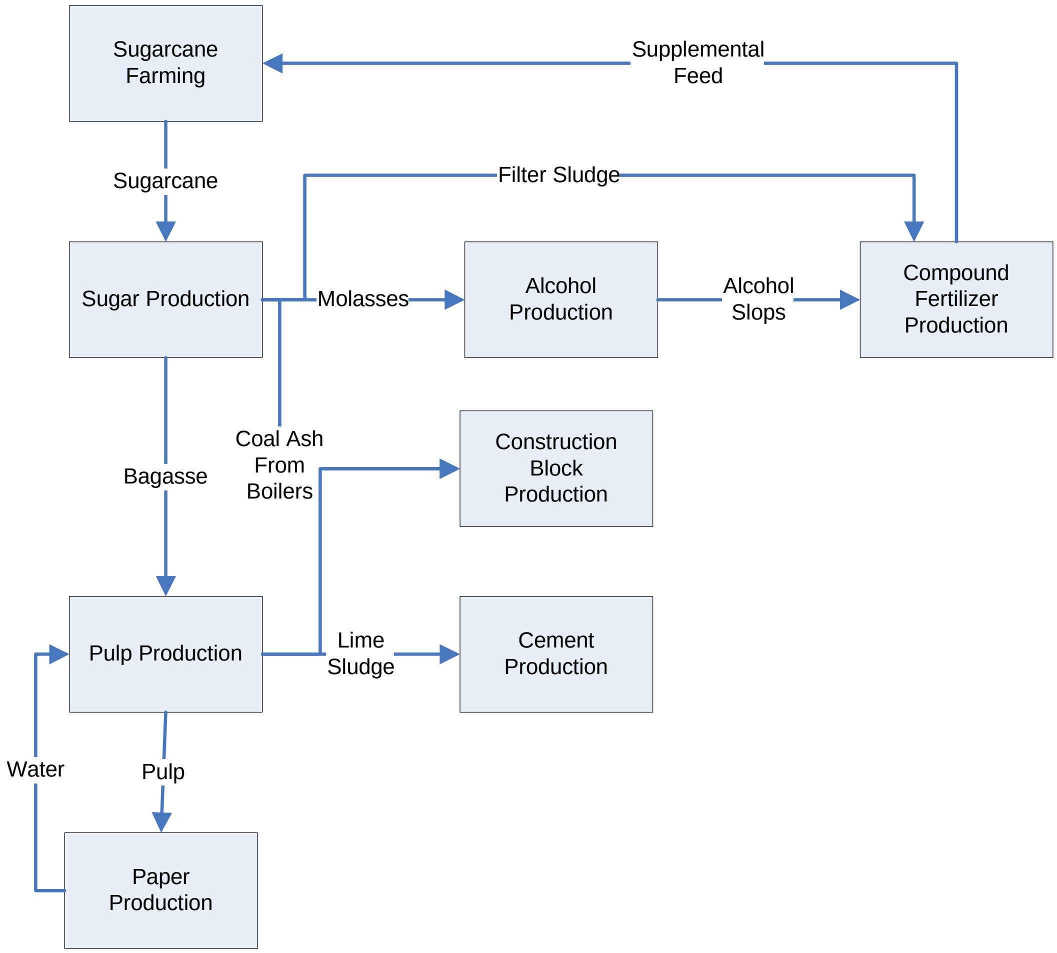

Figure 94: Nanning Sugar Company Symbiosis

20. PV Symbiosis Proposition

Pearce proposes an eco-industrial park built around a multi-gigawatt photovoltaic (PV) module factory (Pearce 2008). The park's three main activities are PV production, municipal waste recycling and agriculture. Pearce's depiction attempts to close the park's material loop by connecting waste generated by PV customers to the park's recycling facility. However, it is unrealistic to expect that the proposed park's local community and tenants would absorb all of a multi-gigawatt facility's PV production. Very little customer waste would find its way to the park's recycling; so, this link has been omitted. As Figure 95 illustrates, the proposed park is a resource cascade almost entirely dedicated to supplying a PV plant

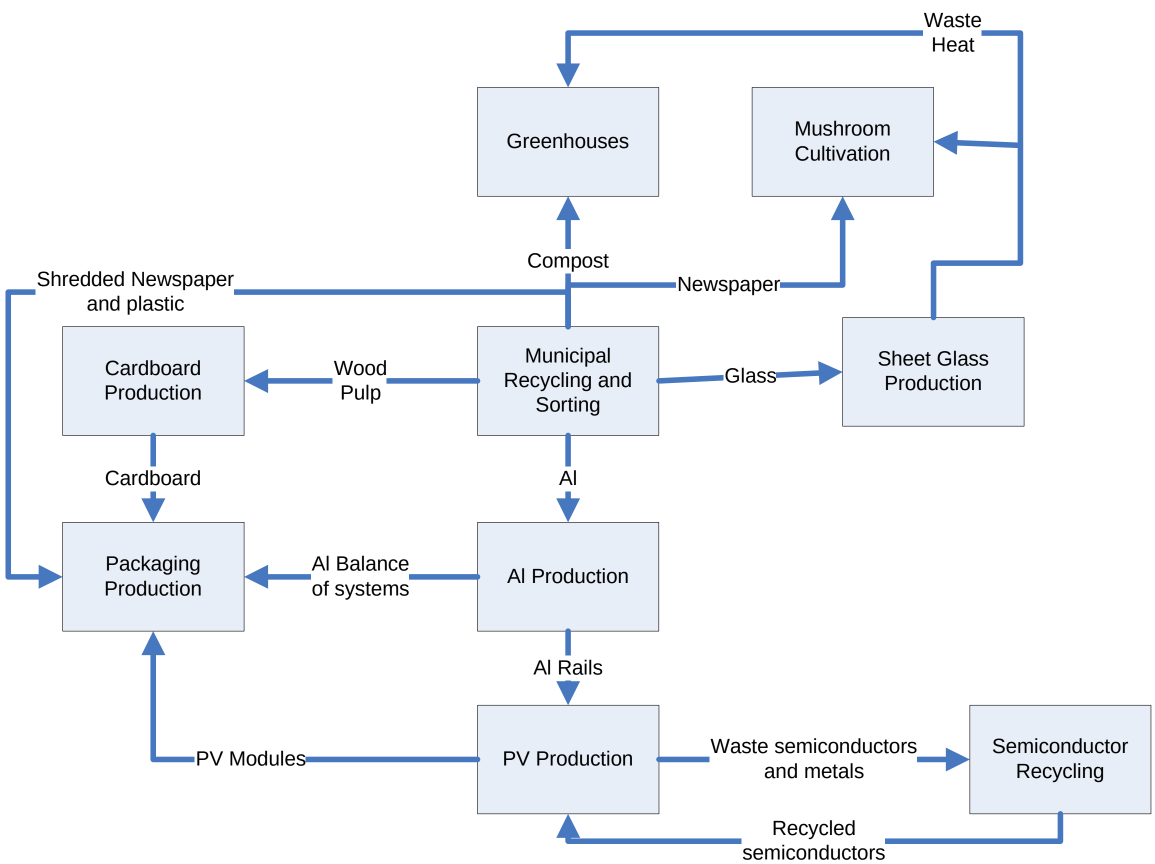

Figure 95: Proposed EIP for photovoltaic module manufacturing

21. Red Hills EcoPlex

A planned eco-industrial park built around a coal-fired power station.

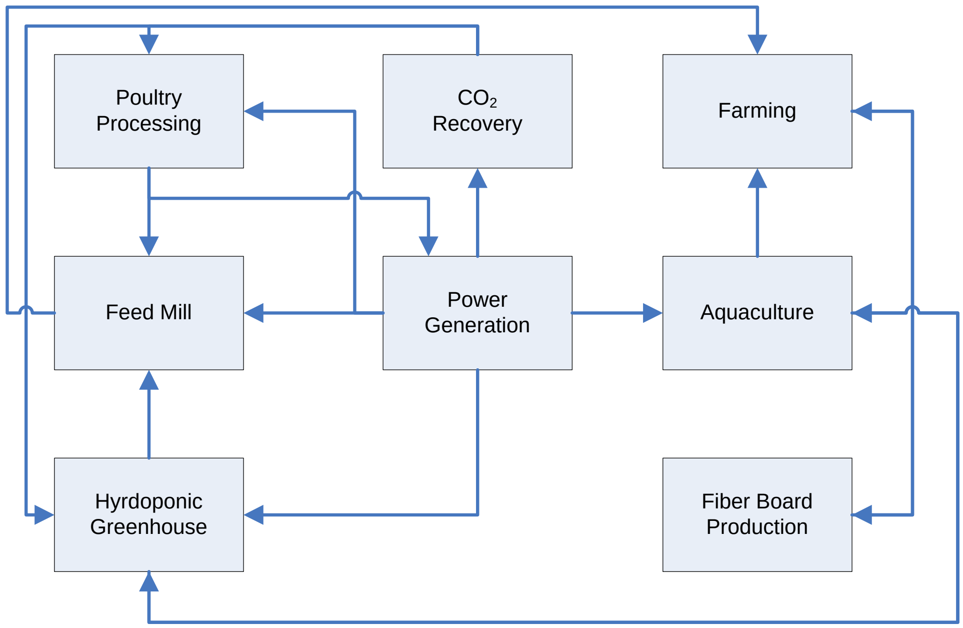

Figure 96: Red Hills EcoPlex diagram

22. Renova Resource Recovery Park

The Renova Resource Recovery Park (RRRP) is an eco-industrial complex proposed for a site on Puerto Rico's northern coast in the county of Arecibo (Abuyuan, et al. 2002). The proposed park's anchor tenant is a waste-to-energy facility intended to incinerate municipal waste and provide steam and electricity. The presence of fallow sugarcane fields near the park also allows for the integration of agricultural components and agriculturally based activities into the eco-industrial park described by Table 278 and Table 279. The complexity of this proposed park mandates presentation of its many links in tabular form.

Table 278: Outputs / emissions utilized in the proposed Renova EIP

#	Activity	Outputs / Emissions	Inputs
1	Agriculture / Aquaculture	Fiber crops, fuel crops, medicinal plants, manure, crop residues	Electricity, graywater, nutrient water
2	Anaerobic Digester	Steam, nutrient water, fiber, biogas	Electricity, steam, nutrient water, manure, crop residue, biosolids
3	Animal Feed Production	Feed	Protein and stillage
4	Compost	Compost	Electricity, nutrient water, fiber
5	Ethanol Manufacture	Steam, nutrient water, ethanol, lignin, protein and sillage	Electricity, steam, fuel crops, cellulosic fiber fines
6	Living Machine	Graywater	Electricity
7	Lumber Mill	Sawdust and scrap	Electricity, fiber crops, lignin
8	Misc. Services	Sewage	Electricity, graywater, ethanol
9	Paper Mill	Steam, sewage, cellulosic fiber fines	Electricity, steam, graywater, fiber crops
10	Pharmaceuticals	Biosolids	Medicinal plants
11	Waste-to-energy	Electricity, steam, sewage	Steam, graywater, lignin, biogas

Table 279: Connections between businesses in the proposed Renova EIP

		From Process #										
		1	2	3	4	5	6	7	8	9	10	11
To Process #	1		1	1	1	1	1					1
	2	1				1					1	1
	3					1						
	4		1									1
	5	1								1		1
	6								1	1		1
	7	1				1						1
	8					1	1					1
	9	1					1	1				1
	10	1										
	11		1			1	1					

23. Seshasayee Paper and Board Ltd. Agro-industrial Eco-complex

An established Indian paper producer cultivated a supply relationship with local sugarcane farmers to guarantee raw material for its paper mill. To efficiently generate the bagasse needed for paper production, Seshasayee Paper built a sugar production facility to process output from local sugarcane fields. Full utilization of the sugar production facility's wastes and byproducts led to establishment of the chain of industries diagramed in Figure 97.

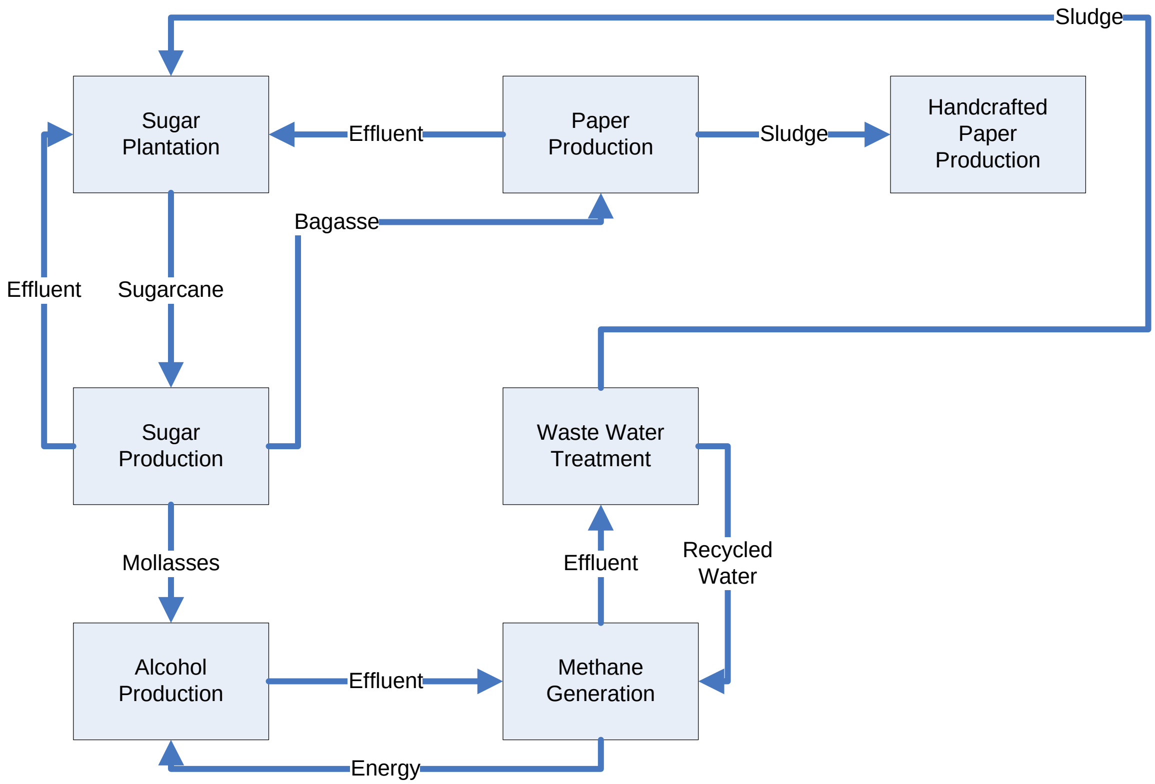

Figure 97: Seshasayee Paper and Board Ltd. agro-industrial ecosystem

24. Stoneyfield Londonderry EIP

The Stoneyfield Londonderry EIP is a planned assemblage of businesses built around an anchoring power plant and multiple agricultural activities.

Table 280: Activities / businesses in the Red Hills EcoPlex EIP

#	Activity / Business
1	Municipal
2	Cement manufacture
3	Fertilizer manufacture
4	Agriculture
5	Composting
6	Insectary
7	Wastewater treatment
8	Food processing
9	Power generation
10	Industry
11	Materials recovery
12	Greenhouses
13	Aquaculture

Table 281: Connections between businesses in the Red Hills EcoPlex EIP

		1	2	3	4	5	6	7	8	9	10	11	12	13
From Process #	1					x						x		
	2			x										
	3				x	x							x	
	4					x								
	5				x									
	6				x								x	
	7				x	x							x	
	8					x		x				x		
	9	x	x	x		x	x	x	x		x		x	x
	10							x				x		
	11													
	12													
	13													

25. Tsumeb Brewery Integrated Bio-system

A development project initiated by the Zero Emissions Research Initiative, the integrated bio-system in Tsumeb, Namibia uses waste grain and water flows to support biogas production and multiple agricultural activities (See Figure 98). Most resources cascade through this system, but biogas from the methane digester can be used in the brewery, adding a measure loop closure to the Tsumeb integrated bio-system.

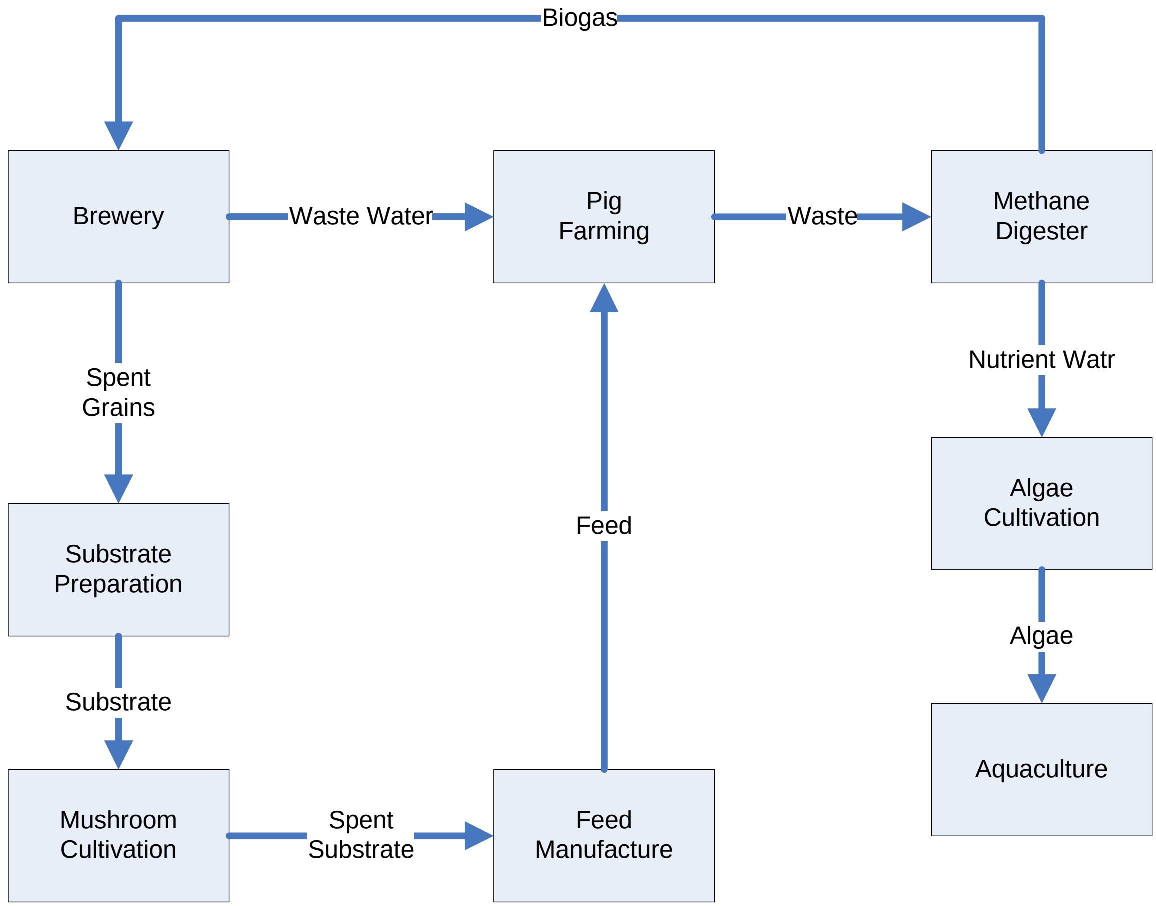

Figure 98: Brewery IBS in Tsumeb, Namibia

26. Ulsan Industrial Park

The Mipo and Onsan industrial parks in Ulsan, South Korea manifest a degree of symbiosis that Korea's National Cleaner Production Center wishes to enhance (Park, et al. 2008). Figure 99 diagrams the existing links between members of the park. The need to remain economically competitive and satisfy environmental regulations motivated the formation of current water, energy and metal connections. The Cleaner Production Center wishes to increase the level of interconnectivity by adding the water and sludge links shown in Figure 100.

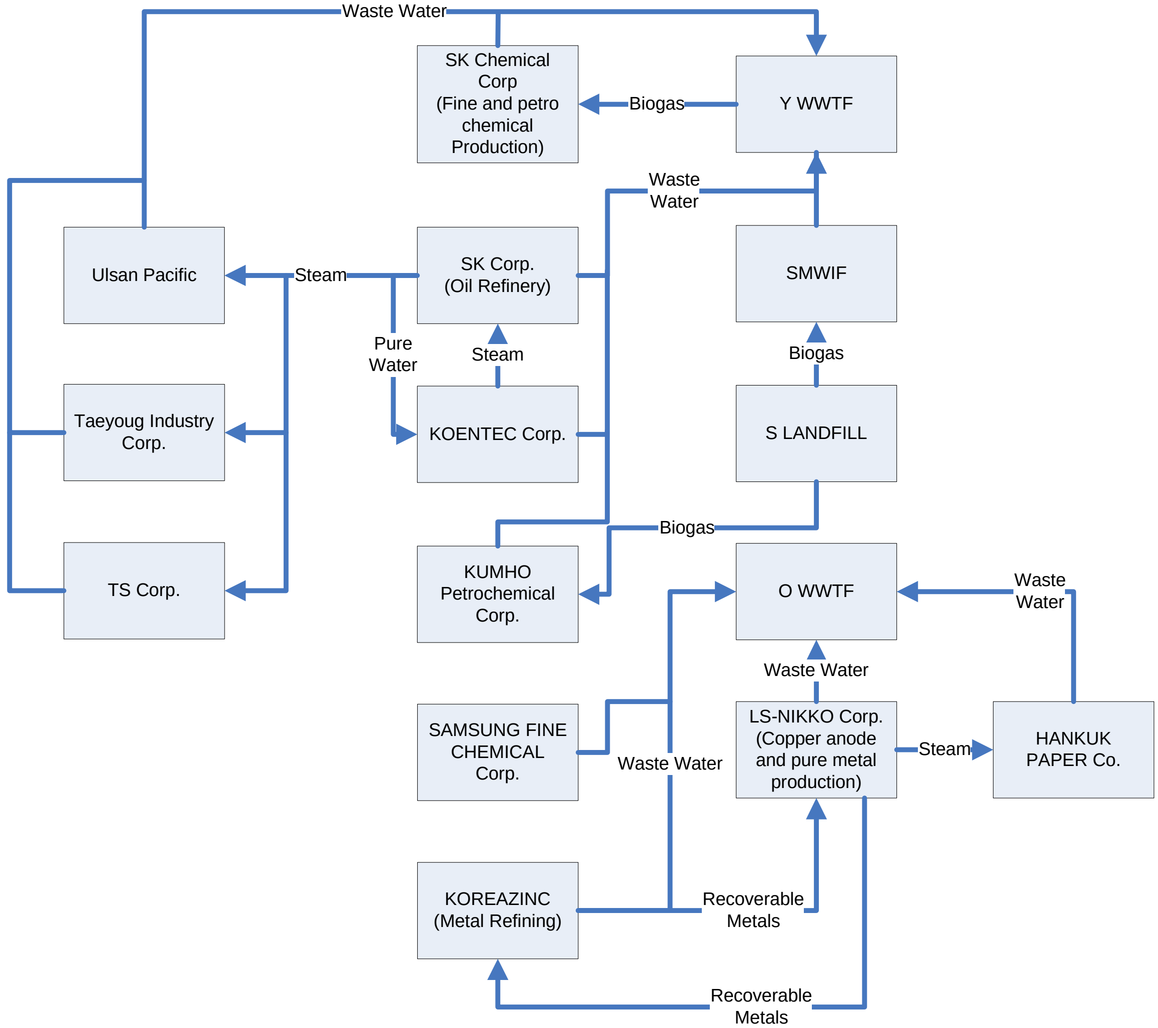

Figure 99: Current configuration of Mipo and Onsan Industrial Parks in Ulsan, South Korea

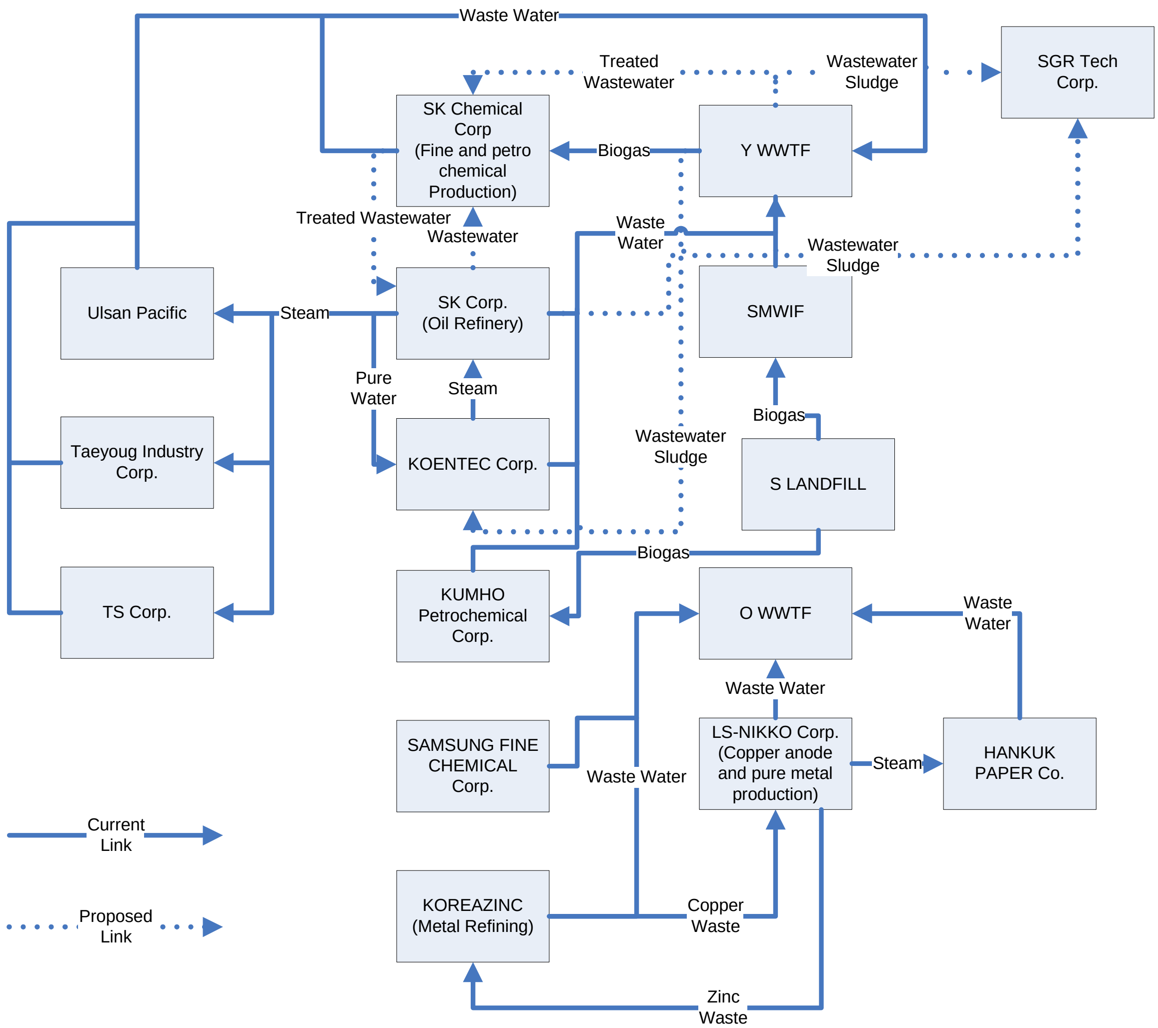

Figure 100: Proposed configuration of Mipo and Onsan Eco-Industrial Park in Ulsan, South Korea

27. Wallingford Eco-Industrial Park

Figure 101 illustrates the composite of proposals made to companies residing in Wallingford, Connecticut's existing industrial park by Johnson and coworkers (Johnson, et al. 2002). The proposal emphasizes use of wastes such as water, scrap metal and ash. Utilization of some of the targeted wastes requires the introduction of facilities that do not currently exist within or near the park.

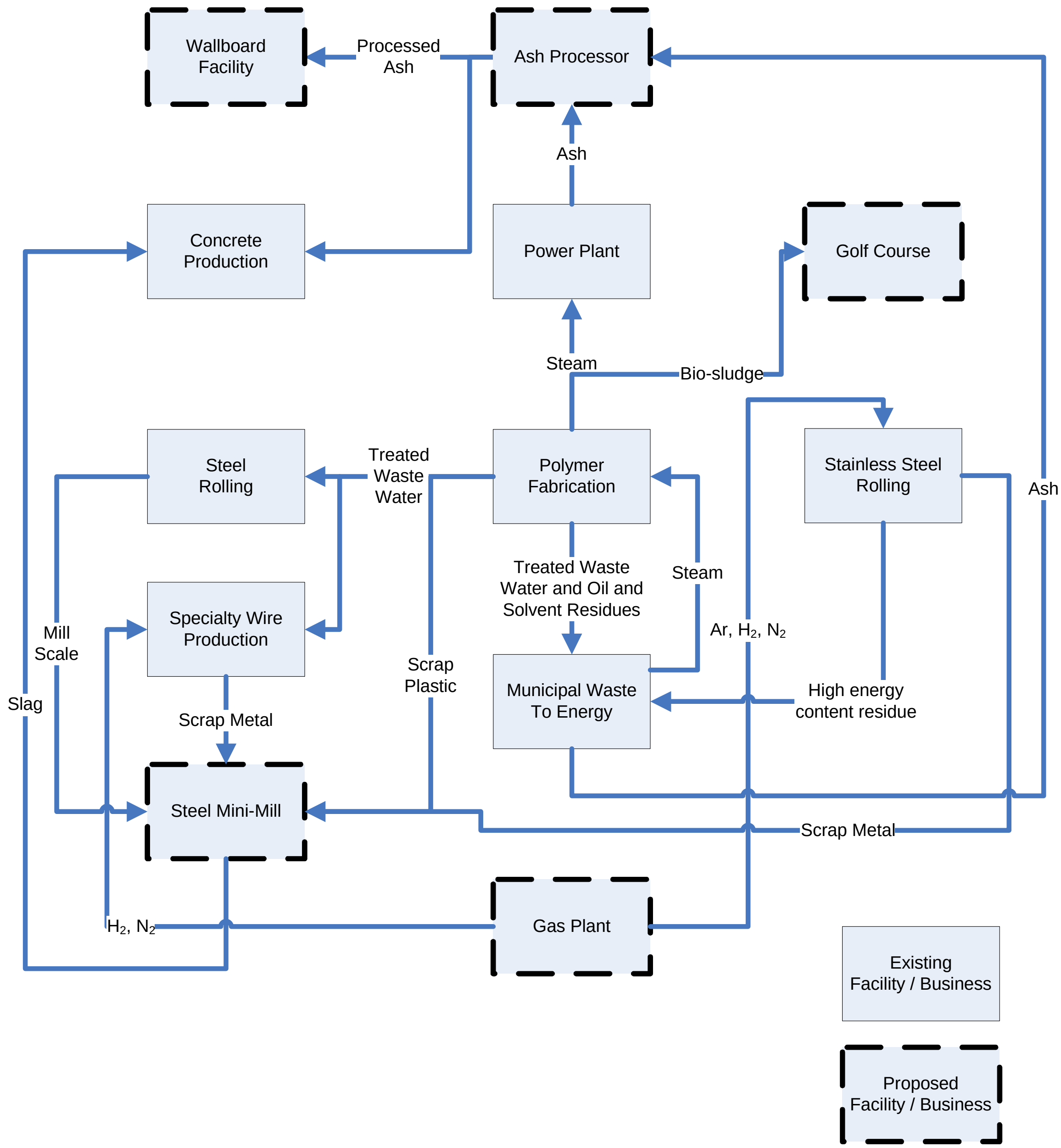

Figure 101: Proposed eco-industrial park for Wallingford, Connecticut

REFERENCES

5th National Nutrition Survey. Philippines.

(2005a). "Biomimicry Guild Database." The Biomimicry Guild LLC. http://database.biomimicry.org

(2005b). "Canadian Community Health Survey." <http://nesstar.library.ubc.ca/webview/index.jsp?object=http://nesstar.library.ubc.ca/obj/fStudy/1010b>.

T. I. C. F. H. a. S. Care. (2005c). Health Survey for England 2004. NHS. http://www.ic.nhs.uk/statistics-and-data-collections/health-and-lifestyles/health-survey-for-england/health-survey-for-england-2004-updating-of-trend-tables-to-include-2004-data>.

(2009). "Envrionmental Product Declaration: Convert Design Product Platform - Carpet Tile InterfaceFlor." InterfaceFLOR, LaGrange, GA.

Abuyuan, A., Hawken, I., Newkirk, M. and Williams, R. (2002). "Waste Equals Food: Developing a Sustainable Agriculture Support Cluster for a Proposed Resource Recovery Park in Puerto Rico." In M. R. Chertow (Ed. Developing Industrial Ecosystems: Approaches, Cases and Tools (pp. 191-214). New Haven: Yale School of Forestry and Environmental Studies.

Ajikumar, P. K., Lakshminarayanan, R. and Suresh, V. (2003). "Mimicking the Formation of Biomineral Composites through Deposition of Calcium Carbonate Thin-Films on Modified Fiber Net Templates." Symposium on Materials Inspired by Biology, San Francisco, California. Materials Research Society, 121-6.

Allen, T. F. H. and Starr, T. B. (1982). Hierarchy: Perspectives for Ecological Complexity. Chicago: The University of Chicago Press.

Archambault, L., Morissette, J. and Bernier-Cardou, M. (1997). Forest succession following a fire in a balsam fir yellow birch stand in the Bas-Saint-Laurent region of Quebec. Forestry Chronicle, 73(6), 702-10.

Arms, K. and Camp, P. S. (1987). Biology (3rd ed.). Philadelphia: Saunders College Publishing.

ASTM (2001).

Auerbach, C. F. and Silverstein, L. B. (2003). Qualitative Data. New York: New York University Press.

Autumn, K. (2007). Gecko Adhesion: Structure, Function, and Applications. Materials Research Society Bulletin, 32, 473-8.

Autumn, K. and Hansen, W. (2006). Ultrahydrophobicity indicates a non adhesive default state in gecko setae. Journal of Comparative Physiology A, 192, 1205-12.

Ayres, R. U. (1994). "Industrial Metabolism: Theory and Policy." In R. U. Ayres and U. E. Simonis (Eds.), Industrial Metabolism: Restructuring for Sustainable Development (pp. 3-20). Tokyo: United Nations University Press.

--- (1995). Life cycle analysis: A critique. Resources, Conservation and Recycling, 14, 199-223.

Azapagic, A. and Clift, R. (1999a). Allocation of Environmental Burdens in Co-Product Systems: Product-related Burdens (Part 1). International Journal of Life Cycle Assessment, 4(6), 357-69.

--- (1999b). Allocation of environmental burdens in multiple-function systems. Journal of Cleaner Production, 7(2), 101-19.
S. P. a. t. E. Ministry of Housing. (2000). Eco-indicator 99 Manual for Designers: A damage oriented method for Life Cycle Impact Assessment. By Baayen, H.: Ministry of Housing, Spatial Planning and the Environment.
Bailey, R., Allen, J. and Bras, B. (2005). Applying Ecological Input-Output Flow Analysis to Material Flows in Industrial Systems: Part 1: Tracing Flows. Journal of Industrial Ecology, 8(1), 45-68.
Bailey, R., Allen, J. K. and Bras, B. (2004a). Applying Ecological Input-Output Flow Analysis to Material Flows in Industrial Systems - Part I: Tracing Flows. Journal of Industrial Ecology, 8(1-2), 45-68.
--- (2004b). Applying Ecological Input-Output Flow Analysis to Material Flows in Industrial Systems - Part II: Flow Metrics. Journal of Industrial Ecology, 8(1-2), 69-91.
Bailey, R. R. (2000). Input-Output Modeling of Material Flows in Industry, Georgia Institute of Technology.
Bandyopadhyay, P. R. (2009). Swimming and Flying in Nature-The Route Toward Applications. The Freeman Scholar Lecture, 131(3).
Barbour, M. G., Burk, J. H., Pitts, W. D., Gilliam, F. S. and Schwartz, M. W. (1999). Terrestrial Plant Ecology. Menlo Park: Addison Wesley Longman, Inc.
Bare, J., Pennington, D. W. and Udo de Haes, H. A. (1999). Life Cycle Impact Assessment Sophistication. International Journal of Life Cycle Assessment, 4(5), 299-306.
Barrett, D. S. (1996). Propulsive Efficiency of a Flexible Hull Undersea Vehicle. dissertation thesis, Massachusetts Institute of Technology.
Barthlott, W. and Neinhuis, C. (1997). Purity of the sacred lotus, or escape from contamination in biological surfaces. Planta, 202(1), 1.
--- (2001). Lotus effect: Nature's model for self-cleaning surfaces. International Textile Bulletin, 47(1), 8.
Bascompte, J. and Jordano, P. (2007). Plant-animal mutualistic networks: The architecture of biodiversity. Annual Review of Ecology Evolution and Systematics, 38, 567-93.
Bascompte, J., Jordano, P. and Olesen, J. M. (2006). Asymmetric Coevolutionary Networks Facilitate Biodiversity Maintenance. Science, 312, 431-3.
Batzer, D. P. and Sharitz, R. R. (2006). Ecology of Freshwater and Estuarine Wetlands. Berkeley: University of California Press.
Baum, C., Meyer, W., Stelzer, R., Fleischer, L.-G. and Siebers, D. (2002a). Average nanorough skin surface of the pilot whale (Globicephala melas, Delphinidae): considerations on the self-cleaning abilities based on nanoroughness. Marine Biology, 140, 653-7.
--- (2002b). Average nanorough skin surface of the pilot whale (Globicephala melas, Delphinidae): considerations on the self-cleaning abilities based on nanoroughness." Marine Biology, 140, 653-7.
Beattie, A. and Ehrlich, P. R. (2001). Wild Solutions: How Biodiversity is Money in the Bank. New Haven: Yale University Press.

Becker, S., Minick, C., Newman, M. and Sherwin, Z. (2002). "AES -Thames and the Stone Container Corporation: The Montville Eco-Industrial System 1997." In M. R. Chertow (Ed. Developing Industrial Ecosystems: Approaches, Cases and Tools (pp. 191-214). New Haven: Yale School of Forestry and Environmental Studies.
Becks, L., Hilker, F. M., Malchow, H., Jurgens, K. and Arndt, H. (2005). Experimental demonstration of chaos in a microbial food web. Nature, 435, 1226-9.
Bell, J. J. (2007). Contrasting patterns of species and functional composition of coral reef sponge assemblages. Marine Ecology Progress Series, 339, 73-81.
Bell, T., Newman, J. A., Silverman, B. W., Turner, S. L. and Lilley, A. K. (2005). The contribution of species richness and composition to bacterial services. Nature, 436, 1157-60.
Bennett, E. B., Heitkamp, E. L., Klee, R. J. and Price-Thomas, P. (2002). "Clark Special Economic Zone: Finding Linkages in an Existing Industrial Estate1998." In M. R. Chertow (Ed. Developing Industrial Ecosystems: Approaches, Cases and Tools (pp. 191-214). New Haven: Yale School of Forestry and Environmental Studies.
Benyus, J. M. (1997). Biomimicry: Innovation Inspired by Nature. New York: HarperCollins.
Berlow, E. L., Neutel, A.-M., Cohen, J. E., De Ruiter, P. C., Ebenman, B., Emmerson, M., Fox, J. W., Jansen, V. A. A., Jones, J. I., Kokkoris, G. D., Logofet, D. O., McKane, A. J., Montoya, J. M. and Petchey, O. (2004). Interaction strengths in food webs: issues and opportunities. Journal of Animal Ecology, 73, 585-98.
Bhushan, B. (2009). Biomimetics: lessons from nature - an overview. Philosophical Transactions of the Royal Society A-mathematical Physical and Engineering Sciences, 367(1893), 1445-86.
Biomimetics, C. f. (2009). "What is Biomimetics." University of Reading. 26 Sept. 2009 http://www.rdg.ac.uk/biomimetics/about.htm
Björklund, A. E. (2002). Survey of Approaches to Improve Reliability in LCA. International Journal of Life Cycle Assessment, 7(2), 64-72.
Bockstael, N. E., Freeman, A. M., Kopp, R. J., Portney, P. R. and Smith, V. K. (2000). On Measuring Economic Values for Nature. Environmental Science and Technology, 34(8), 1384-9.
Boer, I. J. M. d. (2003). Environmental impact assessment of conventional and organic milk production. Livestock Production Science, 80(1-2), 69-77.
Bonsdorff, E. (2006). Zoobenthic diversity-gradients in the Baltic Sea: Continuous post-glacial succession in a stressed ecosystem. Journal of Experimental Marine Biology and Ecology, 330(1), 383-91.
Bowers, J. E., Webb, R. H. and Pierson, E. A. (1997). Succession of desert plants on debris flow terraces, Grand Canyon, Arizona, USA. Journal of Arid Environments, 36(1), 67-86.
Bowyer, A. (2009). "Welcome to the Biomimetics Group." University of Bath. 26 Sept. 2009 http://www.bath.ac.uk./mech-eng/biomimetics/
Brady, T. and McManus, T. (2003). "Design for Environment at Intel." Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan. IEEE, 626-31.

Brentrup, F., Kusters, J., Lammel, J. and Kuhlmann, H. (2002). Life Cycle Impact Assessment of Land Use Based on the Hemeroby Concept. International Journal of Life Cycle Assessment, 7(6), 339-48.

Briand, F. (1983). Environmental Control of Food Web Structure. Ecological Society of America, 64(2), 253-63.

Briand, F. d. r. and Cohen, J. E. (1987). Environmental Correlates of Food Chain Length. Science, 238(4829), 956-60.

Brundtland, G. H. (1987). Our Common Future, Report of the United Nations World Commission on Environment and Development. Oxford: Oxford University Press.

Buchmann, N., Cuddington, K. and Lambrinos, J. (2007). "A Historical Perspective on Ecosystem Engineering." In K. Cuddington, J. E. Byers, W. G. Wilson and A. Hastings (Eds.), Ecosystem Engineers: Plants to Protists (pp. 25-46). Amsterdam: Elsevier.

Cadenasso, M. L., Pickett, S. T. A. and Weathers, K. C. (2004). "Effect of Landscape Boundaries on the Flux of Nutrients, Detritus, and Organisms." In G. A. Polis, M. E. Power and G. R. Huxel (Eds.), Food Webs at the Landscape Level. London: University of Chicago Press.

Campbell, N. A. (1996). Biology (4th ed.). Menlo Park: The Benjamin Cummings Publishing Company, Inc.

Canals, L. M., Bauer, C., Depestele, J., Dubreuil, A., Knuchel, R. F., Gaillard, G., Michelsen, O., Muller-Wenk, R. and Rydgren, B. (2006). Key Elements in a Framework for Land Use Impact Assessment Within LCA. International Journal of Life Cycle Assessment, 11(4), 1-11.

Carr, A. J. P. (1998). Choctaw eco-industrial park: An ecological approach to industrial land-use planning and design. Landscape and Urban Planning (Amsterdam), 42(2-4), 239-57.

Cassie, A. B. D. and Baxter, S. (1944). Wettability of Porous Surfaces. Transactions of the Faraday Society, 40, 546-51.

Cavelaars, A. E. J. M., Kunst, A. E., Geurts, J. J. M., R., C., L., G., U., H., E., L., O., L., A., M., N.K., R., E., R., T., S. and J.P., M. (2000). Persistent Variations in average height between countries and between socio-economic groups: an overview of 10 European countries. Annals of Human Biology, 27(4), 407-21.

Cengel, Y. A. and Boles, M. A. (1998). Thermodynamics: An Engineering Approach (3rd ed.). Boston: McGraw-Hill.

Chaisson, E. J. (2001). Cosmic Evolution: The Rise of Complexity in Nature. Cambridge: Harvard University Press.

Chambers, N., Simmons, C. and Wackernagel, M. (2000). Sharing nature's interest: ecological footprint as an indicator of sustainability. London: Earthscan.

Chase, J. M. (2000). Are there real differences among aquatic and terrestrial food webs. Trends in Ecology & Evolution, 15(10), 408-12.

Chawla, M. K. (Ed. (2003). Monitoring cleanliness and defining acceptable cleanliness levels (Vol. 1). New York: Brill Academic Press.

Chengchun, H. (2001). "Energy environment and agriculture in China." Food and Agricultural Organization of the United Nations. November 3 http://www.fao.org/docrep/T4470E/t4470e0q.htm

Chertow, M. R. (2000). Industrial Symbiosis: Literature and Taxonomy. Annual Review of Energy and Environment, 25, 313-37.
--- (Ed. (2002). Developing Industrial Ecosystems: Approaches, Cases and Tools. New Haven: Yale School of Forestry and Environmental Studies.
Chertow, M. R. and Lombardi, D. R. (2005a). Quantifying economic and environmental benefits of co-located firms. Environmental Science & Technology, 39(17), 6535-41.
Chertow, M. R. and Lombardi, R. D. (2005b). Quantifying economic and environmental benefits of co-located firms. Environmental Science & Technology, 39(17), 6535-41.
Chiu, I. and Shu, L. H. (2004). "Natural language analysis for biomimetic design." Salt Lake City, UT, United States. American Society of Mechanical Engineers, New York, NY 10016-5990, United States, 99.
Ciroth, A., Fleischer, G. and Steinbach, J. (2004). Uncertainty Calculation in Life Cycle Assessments: A combined model of simulation and approximation. International Journal of Life Cycle Assessment, 9(4), 216-26.
Clements, F. E. (1916). Plant Succession: Analysis of the Development of Vegetation. Washington, D.C.: Carnegie Institute.
Congress, U. S. (1992). "Green Products by Design: Choices for a Cleaner Environment." OTA-E-541. Office of Technology Assessment.
Consoli, F., Allen, D., Boustead, I. and Fava, J. (1993). "Guidelines for Life-Cycle Assessment: A 'Code of Practice'." The SETAC Workshop, Sesimbra, Portugal, 31 March - 3 April. Society of Environmental Toxicology And Chemistry (SETAC).
Cooper, J. S. (2003). Specifying Functional Units and Reference Flows for Comparable Alternatives. International Journal of Life Cycle Assessment, 8(6), 337-49.
Cousins, S. H. (1996). "Food Webs: From the Lindeman Paradigm to a Taxonomic General Theory of Ecology." In G. A. Polis and K. O. Winemiller (Eds.), Food Webs: Integration of Patterns & Dynamics (pp. 243-51). New York: Chapman & Hall.
Cowles, H. C. (1911). The Causes of Vegetational Cycles. Annals of the Association of American Geographers, 1, 3-20.
Crutsinger, G. M., Collings, M. D., Fordyce, J. A., Gompert, Z., Nice, C. C. and Sanders, N. J. (2006). Plant Genotypic Diversity Predicts Community Structure and Governs an Ecosystem Process. Science, 313, 966-8.
Curran, M. A. (2006). Co-Product and Input Allocation Approaches for Creating Life Cycle Inventory Data: A Literature Review. International Journal of Life Cycle Assessment, OnlineFirst, pp.14.
Cutkosky, M. R. (2009). Design and fabrication of multi-material structures for bioinspired robots. Philosophical Transactions of the Royal Society A-mathematical Physical and Engineering Sciences, 367(1894), 1799-813.
Darwin, C. (1859). On the Origin of Species or the Preservation of Favoured Races in the Struggle for Life. London: John Murray, Albemarle Street.
--- (1881). The Formation of Vegetable Mould Through the Action of Worms with Observations of their Habitats. London: Murray.

--- (1936). The Origin of Species By Means of Natural Selection or the Preservation of Favored Races in the Struggle for Life and The Descent of Man and Selection in Relation to Sex. New York: Random House, Inc.

de Ruiter, P. C., Neufel, A.-M. and Moore, J. C. (1995). Energetics, Patterns of Interaction Strengths, and Stability in Real Ecosystems. Science, 269, 1257-60.

Denitto, F., Terlizzi, A. and Belmonte, G. (2007). Settlement and primary succession in a shallow submarine cave: spatial and temporal benthic assemblage distinctness. Marine Ecology, 28, 35-46.

"biomimetics."McGraw-Hill Dictionary of Scientific and Technical Terms. 1994a. S. P. Parker. McGraw-Hill Inc.

"bionics."McGraw-Hill Dictionary of Scientific and Technical Terms. 1994b. S. P. Parker. McGraw-Hill Inc.

"biomimetics."Merriam-Webster Online Dictionary. 2009a. Merriam-Webster Online. 26 Sept. 2009. http://www.merriam-webster.com/dictionary/biomimetics

"bionics."Merriam-Webster Online Dictionary. 2009b. Merriam-Webster Online. 26 Sept. 2009. http://www.merriam-webster.com/dictionary/bionics

""biognosis"."Webster's Third New International Dictionary of the English Language Unabridged. 1993a. P. B. Gove. Merriam-Webster Inc.

""homology"."Webster's Third New International Dictionary of the English Language Unabridged. 1993b. P. B. Gove. Merriam-Webster Inc.

""sustainable"."Webster's Third New International Dictionary of the English Language Unabridged. 1993c. P. B. Gove. Merriam-Webster Inc.

"biomimicry."Dictionary.com. 2009. Dictionary.com, LLC. 13 Oct. 2009. http://dictionary.reference.com/browse/biomimicry

Dreyer, L. C., Hauschild, M. Z. and Schierbeck, J. (2006). A Framework for Social Life Cycle Impact Assessment. International Journal of Life Cycle Assessment, 11(2), 88-97.

Dreyer, L. C., Niemann, A. L. and Hauschild, M. Z. (2003). Comparison of Three Different LCIA Methods: EDIP97, CML2001 and Eco-Indicator 99 - Does it matter which you choose? International Journal of Life Cycle Assessment, 8(4), 191-200.

Ebenman, B. and Jonsson, T. (2005). Using community viability analysis to identify fragile systems and keystone species. Trends in Ecology & Evolution, 20(10), 568-75.

Ehrenfeld, J. (1997). The Importance of LCAs - Warts and All. Journal of Industrial Ecology, 1(2), 41-9.

Ehrenfeld, J. and Gertler, N. (1997). Industrial Ecology in Practice: The Evolution of Interdependence at Kalundborg. Journal of Industrial Ecology, 1(1), 67-79.

EIA (2008).

Ekvall, T. and Finnveden, G. (2001). Allocation in ISO 14041 - a critical review. Journal of Cleaner Production, 9, 197-208.

Ekvall, T. and Tillman, A.-M. (1997). Open-Loop Recycling: Criteria for Allocation Procedures. International Journal of Life Cycle Assessment, 2(3), 155-62.

Emblemsvag, J. and Bras, B. (2001). Activity-Based Cost and Environmental Management. Boston: Kluwer Academic Publishers.

EPA, U. S. (1993). "Life-Cycle Design Guidance Manual." US Environmental Protection Agency, Office of Research and Development, Washington DC.
(2006). Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2004. By ---. United States Environmental Protection Agency.
Erkman, S. and Ramaswamy, R. (2000). "Cleaner Production at the System Level: Industrial Ecology as a Tool for Development Planning (Case Studies in India)." 6th International High-level Seminar on Cleaner Production, Montreal, Canada. UNEP, 1-18.
Esty, D. C., Andonov, B., Kim, C., Townsend, J., Srebotnjak, T., Campbell, K., Li, Q., Zhang, B., Goodall, M., Gregg, K., Martinez, M., Levy, M., Sherbinin, A. d., Anderson, B., Saltelli, A., Saisana, M., Nardo, M. and Dahl, A. (2005). "2005 Environmental Sustainability Index: Benchmarking National Environmental Stewardship." Yale Center for Environmental Law and Policy, New Haven.
Fargnoli, M. (2003). "The Assessment of the Environmental Sustainability." Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokoyo, Japan, Dec. 8-11. IEEE, 362-8.
Farrell, A. E., Plevin, R. J., Turner, B. T., Jones, A. D., O'Hare, M. and Kammen, D. M. (2006). Ethanol Can Contribute to Energy and Environmental Goals. Science, 311, 506-8.
Farrow, R. S., Goldburg, C. B. and Small, M. J. (2000). Economic Valuation of the Environment: A Special Issue. Environmental Science & Technology, 34(8), 1381-3.
Fath, B. D. (2007). Structural food web regimes. Ecological Modelling, 208, 391-4.
Fath, B. D. and Halnes, G. (2007). Cyclic energy pathways in ecological food webs. Ecological Modelling, 208(1), 17-24.
Ferrer, G. and Ayres, R. U. (2000). The impact of remanufacturing in the economy. Ecological Economics, 32(3), 413-29.
Field, F., Kirchain, R. and Clark, J. (2001). Life-Cycle Assessment and Temporal Distributions of Emissions. Journal of Industrial Ecology, 4(2), 71-91.
Finkbeiner, M., Hoffman, E. and Kreisel, G. (1997). The Functional Unit in the Life Cycle Inventory Analysis of Degreasing Processes in the Metal-Processing Industry. Environmental Management, 21(4), 635-42.
Finn, J. T. (1976). Measures of ecosystem structure and function derived from analysis of flows. Journal of Theoretical Biology, 56, 363-80.
--- (1977). Flow Analysis: A Method of Tracing Flows Through Ecosystem Models. dissertation thesis, University of Georgia.
Finnveden, G. (2000). On the Limitations of Life Cycle Assessment and Environmental Systems Analysis Tools in General. International Journal of Life Cycle Assessment, 5(4), 229-38.
--- (2005b). The Resource Debate Needs to Continue. International Journal of Life Cycle Assessment, 10(5), 372.
Finnveden, G., Hofstetter, P., Bare, J., Basson, L., Ciroth, A., Mettier, T., Seppälä, J., Johansson, J., Norris, G. and Volkwein, S. (2002). "Normalisation, Grouping, and Weighting in Life Cycle Impact Assessment." In H. A. Udo de Haes, G.

Finnveden, M. Goedkoop, M. Hauschild, E. G. Hertwich, P. Hofstetter, O. Jolliet, W. Klopffer, W. Krewitt, E. Lindeijer, R. Muller-Wenk, S. I. Olsen, D. W. Pennington, J. Potting and B. Steen (Eds.), Life Cycle Impact Assessment: Striving towards Best Practice. Pensacola: Society of Environmental Toxicology and Chemistry.

Finnveden, G. and Nilsson, M. (2005a). Site-dependent Life-Cycle Impact Assessment in Sweden. International Journal of Life Cycle Assessment, 10(4), 235-9.

Foley, J. A., DeFries, R., Asner, G., Barford, C., Bonan, G., Carpenter, S. R., Chapin, F. S., Coe, M. T., Daily, G. C., Gibbs, H. K., Helkowski, J. H., Holloway, T., Howard, E. A., Kucharik, C. J., Monfreda, C., Patz, J. A., Prentice, I. C., Ramankutty, N. and Snyder, P. K. (2005). Global Consequences of Land Use. Science, 309, 570-4.

Frischknecht, R., Althaus, H.-J., Bauer, C., Doka, G., Heck, T., Jungbluth, N., Kellenberger, D. and Nemecek, T. (2007). The Environmental Relevance of Capital Goods in Life Cycle Assessments of Products and Services. International Journal of Life Cycle Assessment, OnlineFirst, 1-11.

Frosch, R. A., Bonner, D. C., Carberry, J. B., Carothers, L., Ditz, D., Gladwin, T. N., Graedel, T. E., Green, C., Gustafson, R. R., Leake, M. J., Mayer, D. W., Morgenstern, R. D., Powers, W. F. and Williams, D. K. (1999). Industrial Environmental Performance Metrics: Challenges and Opportunities. Washington, D.C.: National Academy Press.

Furuholt, E. (1995). Life cycle assessment of gasoline and diesel. Resources, Conservation and Recycling, 14, 251-63.

Gamlin, L. and Vines, G. (Eds.). (1987). The Evolution of Life. New York: Oxford University Press.

Geisler, G., Hellweg, S. and Hungerbühler, K. (2004). Uncertainty Analysis in Life Cycle Assessment (LCA): Case Study on Plant-Protection Products and Implications for Decision Making. International Journal of Life Cycle Assessment, 10(3), 184-92.

Gerardin, L. (1968). Bionics (P. Priban, Trans.). New York: McGraw-Hill Book Company.

GFN (2008).

Glaser, B. G. and Strauss, A. L. (1967). The Discovery of Grounded Theory. Chicago: Aldine Publishing Company.

Gleason, H. A. (1927). Further Views on the Succession-Concept. Ecology, 8(3), 299-326.

Golden, I. (2006). "Background." University of Maryland. 12 Oct. 2009 http://www.bioinspired.umd.edu/

Gotelli, N. J. and Colwell, R. K. (2001). Quantifying biodiversity: procedures and pitfalls in the measurement and comparison of species richness. Ecology Letters, 4, 379-91.

Graedel, T. E. (1998a). Streamlined Life-Cycle Assessment. Upper Saddle River: Prentice Hall.

--- (1998b). Streamlined Life-Cycle Assessment. Upper Saddle River, NJ: Prentice Hall.

Graedel, T. E. and Allenby, B. R. (1995). Industrial Ecology. Englewood Cliffs: Prentice Hall.

Grandjean, E. (1988). Fitting the task to the man: a textbook of occupational ergonomic (4th ed.). London: Taylor and Francis.
Groenendijk, M. and Meijer, J. (2006). Microstructuring using femtosecond pulsed laser ablation. Journal of Laser Applications, 18(3), 227-35.
Guidry, C. (2008). Modified Comparative Life Cycle Assessment of End-of-Life Options for Post-Consumer Products in Urban Regions. Masters thesis, Georgia Institute of Technology.
Gutowski, T. G. (2008).
Gutzmer, W. (2005). "Biomimetics Defined." Schmitt Biomimetic Charitable Foundation. 28 Sept. 2009 http://www.otto-schmitt.org/OttoPagesFinalForm/BiomimeticsDefinition.htm
Hall, C. A. S. (Ed. (1995). Maximum power: the ideas and applications of H.T. Odum. Niwot: University Press of Colorado.
--- (2004). The continuing importance of maximum power. Ecological Modelling, 178(1-2), 107-13.
Hammerschlag, R. (2006). Ethanol's Energy Return on Investment: A Survey of the Literature 1990-Present. Environmental Science & Technology, 40(6), 1744-50.
Hammitt, J. K. (2002). QALYs Versus WTP. Risk Analysis, 22(5), 985-1001.
Hansen, W. R. and Autumn, K. (2005). Evidence for self-cleaning in gecko setae. Proceedings of the National Academy of Sciencies, 102, 385-9.
Hardy, C. (2001). Industrial Ecosystems and Food Web Theory. Masters thesis, Yale University.
Hardy, C. and Graedel, T. E. (2002). Industrial Ecosystems as Food Webs. Journal of Industrial Ecology, 6(1), 29-38.
Hastings, A., Byers, J. E., Crooks, J. A., Jones, C. G., Lambrinos, J. G., Talley, T. S. and Wilson, W. G. (2007). Ecosystem engineering in space and time. Ecology Letters, 10, 153-64.
Hau, J. L. and Bakshi, B. R. (2004). Expanding exergy analysis to account for ecosystem products and services. Environmental Science and Technology, 38(13), 3768-77.
Hauschild, M. and Wenzel, H. (2000a). "Life Cycle Assessment - Environmental Assessment of Products." In S. E. Jorgensen (Ed. A Systems Approach to the Environmental Analysis of Pollution Minimization (pp. 155-89). Boca Raton: Lewis Publishers.
--- (2000b). "Life Cycle Assessment - Environmental Assessment of Products." In S. E. Jørgensen (Ed. A Systems Approach to the Environmental Analysis of Pollution Minimization
(pp. 155-89). Boca Raton: Lewis Publishers.
Hayter, A. (2002). Probability and Statistics for Engineers and Scientists (2nd ed.). Pacific Grove: DUXBURY Thomson Learning.
Heijungs, R. and Frischknecht, R. (1998). A Special View on the Nature of the Allocation Problem. International Journal of Life Cycle Assessment, 3(5), 321-32.
Heijungs, R., Guinée, J. B., Kleijn, R. and Rovers, V. (2006). Bias in Normalization: Causes, Consequences, Detection and Remedies. International Journal of Life Cycle Assessment(In press: available online).

Hellweg, S. (2001). Time and Site-Dependent Life Cycle Assessment of Thermal Waste Treatment Processes. International Journal of Life Cycle Assessment, 6(1), 46.

Hellweg, S., Demou, E., Scheringer, M., McKone, T. E. and Hungerbuhler, K. (2005). Confronting Workplace Exposure to Chemicals with LCA: Examples of Trichloroethylene and Perchloroethylene in Metal Degreasing and Dry Cleaning

Environmental Science & Technology, 39(19), 7741-8.

Hendrickson, C., Horvath, A., Joshi, S. and Lave, L. (1998). Economic Input-Output Models for Environmental Life-Cycle Assessment. Environmental Science & Technology, 32(7).

Hertwich, E. G. (2005). Life Cycle Approaches to Sustainable Consumption: A Critical Review. Environmental Science & Technology, 39(13), 4673-84.

Hertwich, E. G. and Hammitt, J. K. (2001). A Decision-Analytic Framework for Impact Assessment - Pat 1: LCA and Decision Analysis. International Journal of Life Cycle Assessment, 6(1), 5-12.

Hettelingh, J.-P., Posch, M. and Potting, J. (2005). Country-dependent Characterisation Factors for Acidification in Europe: A Critical Evaluation. International Journal of Life Cycle Assessment, 10(3), 177-83.

Heuvelmans, G., Muys, B. and Feyen, J. (2005). Extending the Life Cycle Methodology to Cover Impacts of Land Use Systems on the Water Balance. International Journal of Life Cycle Assessment, 10(2), 113-9.

Hischier, R. and Reichart, I. (2003). Multifunctional Electronic Media - Traditional Media: The Problem of an Adequate Functional Unit. International Journal of Life Cycle Assessment, 8(4), 201-8.

Hooper, D. U., Chapin III, F. S., Ewel, J. J., Hector, A., Inchausti, P., Lavorel, S., Lawton, J. H., Lodge, D. M., Loreau, M., Naeem, S., Schmid, B., Setala, H., Symstad, A. J., Vandermeer, J. and Wardle, D. A. (2005). Effects of Biodiversity on Ecosystem Functioning: A Consensus of Current Knowledge. Ecological Monographs, 75(1), 3-35.

Huie, J. C. (2003). Guided molecular self-assembly: a review of recent efforts. Smart Materials and Structures, 12, 264-71.

Huijbreghts, M. A., Schopp, W., Verkuijlen, E., Heijungs, R. and Reijnders, L. (2001). Spatially Explicit Characterization of Acidifying and Eutrophying Air Pollution in Life-Cycle Assessment. Journal of Industrial Ecology, 4(3), 75-91.

Huijbreghts, M. A. and Seppala, J. (2000). Towards Region-Specific, European Fate Factors for Airborne Nitrogen Compounds Causing Aquatic Eutrophication. International Journal of Life Cycle Assessment, 5(2), 65-7.

Huijbregts, M. A. J. (1998). Part I: A General Framework for the Analysis of Uncertainty and Variability in Life Cycle Assessment. International Journal of Life Cycle Assessment, 3(5), 273-80.

Huisman, J. and Stevels, A. (2003). "Balancing Design Strategies and End-of-Life Processing." Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, Dec. 8-11. IEEE, 40-7.

Hunkeler, D. (2006). Societal LCA Methodology and Case Study

International Journal of Life Cycle Assessment, 11(6), 371-82.

Hunkeler, D. and Rebitzer, G. (2003). Life Cycle Costing - Paving the Road to Sustainable Development? International Journal of Life Cycle Assessment, 8(2), 109-10.
--- (2005). The Future of Life Cycle Assessment. International Journal of Life Cycle Assessment, 10(5), 305-8.
International Standards Organization (1997). "ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework." ISO 14040:1997(E). International Standards Organization.
Intlekofer, K. (2009).
ISO (1997). "ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework." ISO 14040:1997(E). International Standards Organization.
--- (1998). "ISO 14041: Environmental Management - Life Cycle Assessment - Goal and Scope Definition and Inventory Analysis." ISO 14041:1998(E). International Standards Organization.
--- (2000). "ISO 14042: Environmental Management - Life Cycle Assessment - Life cycle impact assessment." ISO 14042:2000(E). International Standards Organization.
--- (2000a). "ISO 14042: Environmental Management - Life Cycle Assessment - Life cycle impact assessment." ISO 14042:2000(E). International Standards Organization.
--- (2000b). "ISO 14043: Environmental Management - Life Cycle Assessment - Life cycle interpretation." ISO 14043:2000(E). International Standards Organization.
--- (2006).
--- (2006a). "ISO 14040: Environmental Management - Life Cycle Assessment - Principles and Framework." ISO 14040:2006(E). International Standards Organization.
--- (2006b). "ISO 14044: Environmental Management - Life Cycle Assessment - Requirements and Guidelines." ISO 14044:2006(E). International Standards Organization.
Jaax, K. N. and Hannaford, B. (2004). "Mechatronic Design of an Actuated Biomimetic Length and Velocity Sensor." Transactions on Robotics and Automation. IEEE, 390-8.
Jacobsen, N. B. (2006). Industrial symbiosis in Kalundborg, Denmark - A quantitative assessment of economic and environmental aspects. Journal of Industrial Ecology, 10(1-2), 239-55.
Jensen, A. A., Elkington, J., Christiansen, K., Hoffmann, L., Moller, B. T., Schmidt, A. and Dijk, F. v. (1997a). Life Cycle Assessment (LCA) - A guide to approaches, experiences and information sources. Soborg, Denmark: dk-TEKNIK Energy & Environment.
Jensen, A. A., Hoffman, L., Møller, B. T., Schmidt, A., Christiansen, K., Elkington, J. and van Dijk, F. (1997b). "Life cycle assessment (LCA): A guide to approaches, experiences, and information sources." European Environmental Agency, Copenhagen.

Jeswiet, J. and Hauschild, M. (2005). EcoDesign and future environmental impacts. Materials and Design, 26, 629-34.

Jofre, S., Tsunemi, K. and Morioka, T. (2003). "A New Eco-Design to Assess Sustainable Environmental Innovation." Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, Dec. 8-11. IEEE, 81-8.

Johnson, E. A. and Miyanishi, K. (2007). Plant Disturbance Ecology: The Process and the Response. Amsterdam: Elsevier.

Johnson, S., Stewart, S., Tierney, R. and Walker, A. (2002). "Wallingford, Connecticut Eco-Industrial Park: A Question of Scale." In M. R. Chertow (Ed. Developing Industrial Ecosystems: Approaches, Cases and Tools (pp. 191-214). New Haven: Yale School of Forestry and Environmental Studies.

Jolliet, O., Müller-Wenk, R., Bare, J., Brent, A., Goedkoop, M., Heijungs, R., Itsubo, N., Peña, C., Pennington, D. W., Potting, J., Rebitzer, G., Stewart, M., Udo de Haes, H. A. and Weidema, B. (2004). The LCIA Midpoint-damage Framework of the UNEP/SETAC Life Cycle Initiative. International Journal of Life Cycle Assessment, 9(6), 394-404.

Jones, C. G. and Gutierrez, J. L. (2007). "On the Purpose, Meaning and Usage of the Physical Ecosystem Engineering Concept." In K. Cuddington, J. E. Byers, W. G. Wilson and A. Hastings (Eds.), Ecosystem Engineers: Plants to Protists (pp. 3-24). Amsterdam: Elsevier.

Jones, C. G., Lawton, J. H. and Shachak, M. (1994). Organisms as ecosystem engineers. Oikos, 69, 373-86.

Jordano, P., Bascompte, J. and Olesen, J. M. (2003). Invariant properties in coevolutionary networks of plant-animal interactions. Ecology Letters, 6(1), 69-81.

Jorgensen, S. E. and Fath, B. D. (2006). Examination of ecological networks. Ecological Modelling, 196(3-4), 283-8.

Joslyn, C. and Booker, J. (2004). "Generalized Information Theory for Engineering Modeling and Simulation." In E. Nikolaidis, D. Ghiocel and S. Singhal (Eds.), Engineering Design Reliability Handbook (pp. 9:1 - 9:40). CRC Press.

journals, I. o. P. e. (2009). "Journal Scope." Institute of Physics. http://www.iop.org/EJ/journal/-page=scope/1748-3190

Kahmen, A., Perner, J. and Buchmann, N. (2005). Diversity-dependent productivity in semi-natural grasslands following climate perturbations. Functional Ecology, 19, 594-601.

Kahneman, D. and Knetsch, J. L. (1992). Valuing public goods: The purchase of moral satisfaction. Journal of Environmental Economics and Management, 22(1), 57-70.

Kaly, U., Pratt, C. and Mitchell, J. (2004). "The Demonstration Environmental Vulnerability Index (EVI) 2004." SOPAC Technical Report 384 South Pacific Applied Geoscience Commission.

Keeney, R. L. and Raiffa, H. (1976). Decisions with Multiple Objectives : Preferences and Value Tradeoffs. New York: Wiley.

Keoleian, G. A. (1998). Is Environmental Improvement in Automotive Design Highly Constrained? Journal of Industrial Ecology, 2(2), 103-18.

Kerwitt, W., Trukenmuller, A., Bachmann, T. M. and Heck, T. (2001). Country-specific Damage Factors for Air Pollution: A Step Toward Site-Dependent Life Cycle Impact Assessment. International Journal of Life Cycle Assessment, 6(4), 199-210.

Kiessling, W. (2005). Long-term relationships between ecological stability and biodiversity in Phanerozoic reefs. Nature, 433, 410-3.

Kim, S. and Dale, B. E. (2006). Ethanol Fuels: E10 or E85 - Life Cycle Perspectives. International Journal of Life Cycle Assessment, 11(2), 117-21.

Kim, T.-H. (2008). Investigations into the design principles in the chemotactic behavior of Escherichia coli. Biosystems, 91(1), 171-82.

Kim, Y.-y. and Gower, L. B. (2003). "Formation of Complex Non-Equilibrium Morphologies of Calcite via Biomimetic Processing." Symposium on Materials Inspired by Biology, San Francisco, California. Materials Research Society, 141-8.

Kirwan, L., Luscher, A., Sebastia, M. T., Finn, J. A., Collins, R. P., Porqueddu, C., Helgadottir, A., Baadshaug, O. H., Brophy, C., Coran, C., Dalmannsdottir, S., Delgado, I., Elgersma, A., Fothergill, M., Franklow-Lindberg, B. E., Golinski, P., Grieu, P., Gustavsson, A. M., Hoglind, M., Huguenin-Elie, O., Iliadis, C., Jorgensen, M., Kadziuliene, Z., Karyotis, T., Lunnan, T., Malengier, M., Maltoni, S., Meyer, V., Nyfeler, D., Nykanen-Kurki, P., Parente, J., Smit, H. J., Thumm, U. and Connolly, J. (2007). Evenness drives consistent diversity effects in intensive grassland systems across 28 European sites. Journal of Ecology, 95, 530-9.

Knight, T. M., McCoy, M. W., Chase, J. M., McCoy, K. A. and Holt, R. D. (2005). Trophic cascades across ecosystems. Nature, 437, 880-3.

Knight, W. and Curtis, M. (2002). "Measuring your ecodesign." Manufacturing Engineer, 64-9.

Korhonen, J. and Snakin, J. P. (2005). Analysing the evolution of industrial ecosystems: concepts and application. Ecological Economics, 52(2), 169-86.

Laland, K. N., Odling-Smee, F. J. and Feldman, M. W. (1999). Evolutionary consequences of niche construction and their implications for ecology. Proceedings of the National Academy of Sciencies, 96, 10242-7.

Lavelle, P., Barot, S., Blouin, M., Decaens, T., Jimenez, J. J. and Jouquet, P. (2007). "Earthworms as key actors in self-organized soil systems." In K. Cuddington, J. E. Byers, W. G. Wilson and A. Hastings (Eds.), Ecosystem Engineers: Plants to Protists (pp. 77-106). Amsterdam: Elsevier.

Lee, J., Sponberg, S. N., Loh, O. Y., Lamperski, A. G., Full, R. J. and Cowan, N. J. (2008). Templates and Anchors for Antenna-Based Wall Following in Cockroaches and Robots. IEEE Transactions on Robotics, 24(1), 130-43.

Lee, J. J., O'Callaghan, P. and Allen, D. (1995). Critical review of life cycle analysis and assessment techniques and their application to commercial activities. Resources, Conservation and Recycling, 13, 37-56.

Legendre, P. and Legendre, L. (1998). Numerical Ecology: Developments in Environmental Modeling 20 (2nd ed.). Amsterdam: Elsevier.

Lent, T. (2003). "Toxic Data Bias and the Challenges of Using LCA in the Design Community." GreenBuild 2003, Pittsburg, PA.
Lenzen, M. (2000). Errors in Conventional and Input-Output-based Life-Cycle Inventories. Journal of Industrial Ecology, 4(4), 127-48.
Leontief, W. W. (1936). Quantitative input-output relations in the economic system of the United States. The Review of Economics and Statistics, 18, 105-25.
Lifset, R. (1997). A Metaphor, a Field and a Journal. Journal of Industrial Ecology, 1(1), 1-4.
--- (2004). Probing Metabolism. Journal of Industrial Ecology, 8(3), 1-3.
Lindeijer, E. (2000). Review of land use impact methodologies. Journal of Cleaner Production, 8, 273-81.
Lindeman, R. L. (1942). The Trophic-Dynamic Aspect of Ecology. Ecology, 23(4), 399-417.
Lloyd, S. M. and Ries, R. (2007). Characterizing, Propagating, and Analyzing Uncertainty in Life-Cycle Assessment: A Survey of Quantitative Approaches. Journal of Industrial Ecology, 11(1), 161-79.
Lotka, A. J. (1922a). Contribution to the Energetics of Evolution. Proceedings of the National Academy of Sciencies, 8, 147-51.
--- (1922b). Natural Selection as a Physical Principle. Proceedings of the National Academy of Sciencies, 8, 151-4.
Maddocks, A. S. and Harris, A. T. (2009). Biotemplated synthesis of novel porous SiC. Materials Letters, 63, 748-50.
Maherali, H. and Klironomos, J. N. (2007). Influence of Phylogeny on Fungal Community Assembly and Ecosystem Functioning. Science, 316, 1746-8.
Mak, T. W. and Shu, L. H. (2004). Abstraction of biological analogies for design. CIRP Annals - Manufacturing Technology, 53(1), 117.
Makarieva, A. M., Gorshkov, V. G. and Li, B.-L. (2005a). Biochemical universality of living matter and its metabolic implications. Functional Ecology, 19, 547-57.
--- (2005b). Energetics of the smallest: do bacteria breathe at the same rate as whales? Proceedings of the Royal Society B, 272, 2219-24.
Makino, Y., Ono, N., Ando, S., Sano, F. and Toba, S. (2002). "Bond Conduction-like Acoustic Sensor System for Evaluating Crispness." 41st Society of Instrumentation and Control Engineering Annual Conference, Osaka, Japan, Aug. 5-7. SICE, 2163-6.
Malak, R. J. J. (2008). USING PARAMETERIZED EFFICIENT SETS TO MODEL ALTERNATIVES FOR SYSTEMS DESIGN DECISIONS, Georgia Institute of Technology.
Margaliot, M. (2008). Biomimicry and fuzzy modeling. A match made in heaven, 3(3), 38-48.
Masera, D. (2003). "Eco-design a Key Factor for Micro and Small Enterprise Development." Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing
Tokyo, Japan, Dec. 8-11. IEEE, 544-51.

Matthews, H. S. and Chambers, G. C. (1997). "Unraveling the Environmental Product Design Paradox." Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment San Francisco, CA, USA, May 5-7. 13-8.

Matthews, H. S. and Lave, L. B. (2000). Applications of Environmental Valuation for Determining Externality Costs. Environmental Science & Technology, 34(8), 1390-5.

Matthews, H. S. and Small, M. J. (2001). Extending the Boundaries of Life-Cycle Assessment through Environmental Economic Input-Output Models. Journal of Industrial Ecology, 4(3), 7-10.

Maurice, B., Frischknecht, R., Coelho-Schwirtza, V. and Hungerbühler, K. (2000). Uncertainty analysis in life cycle inventory. Application to the production of electricity with French coal power plants. Journal of Cleaner Production, 8(2), 95-108.

May, R. M. (1972). Will a Large Complex System be Stable? Nature, 238, 413-4.

McCleese, D. and LaPuma, P. (2002). Using Monte Carlo Simulation in Life Cycle Assessment for Electric and Internal Combustion Vehicles. International Journal of Life Cycle Assessment, 7(4), 230-6.

McCook, L. J. (1994). Understanding ecological community succession: causal models and theories, a review. Vegetatio, 110, 115-47.

McDonald, R. I., Halpin, P. N. and Urban, D. L. (2007). Monitoring succession from space: A case study from the North Carolina Piedmont Applied Vegetation Science, 10(2), 193-203.

Merriam, S. B. (1998). Qualitative Research and Case Study Applications in Education. San Francisco: Jossey-Bass Publishers.

Mettier, T., Scholz, R. W. and Tietje, O. (2006). Measuring Preferences on Environmental Damages in LCIA - Part 1: Cognitive Limits in Panel Surveys. International Journal of Life Cycle Assessment, 11(6), 394-402.

Mettier, T. M. and Hofstetter, P. (2004). Survey Insights into Weighting Environmental Damages: Influence of Context and Group. Journal of Industrial Ecology, 8(4), 189-209.

Mirata, M. and Emtairah, T. (2005). Industrial symbiosis networks and the contribution to environmental innovation - The case of the Landskrona industrial symbiosis programme. Journal of Cleaner Production, 13(10-11), 993-1002.

Mistree, F., Hughes, O. F. and Bras, B. (1993). "Compromise Decision Support Problem and the Adaptive Linear Programming Algorithm." In M. P. Kamat (Ed. Structural Optimization: Status and Promise (pp. 247-89). Washington, D.C.: American Institute of Aeronautics and Astronautics.

Mistree, F., Patel, B. and Vadde, S. (1994). On Modeling Mulitple Objectives and Multi-Level Decisions in Concurrent Design. Advances in Design Automation, 2, 151-61.

Miyake, Y., Hiura, T., Kuhara, N. and Nakano, S. (2003). Succession in a stream invertebrate community: A transition in species dominance through colonization. Ecological Research, 18(5), 493-501.

Mongelli, I., Suh, S. and Huppes, G. (2005). A Structure Comparison of two Approaches to LCA Inventory Data, Based on the MIET and ETH Databases. International Journal of Life Cycle Assessment, 10(5), 317-24.

Montoya, J. M., Pimm, S. L. and Sole, R. V. (2006). Ecological networks and their fragility. Nature, 442, 259-64.

Mori, A. S., Osono, T., Uchida, M. and Kanda, H. (2007). Changes in the structure and heterogeneity of vegetation and microsite environments with the chronosequence of primary succession on a glacier foreland in Ellesmere Island, high arctic Canada. Ecological Research, 23(2), 363-70.

Moriguchi, Y. and Terazono, A. (2000). A Simplified Model for Spatially Differentiated Impact Assessment of Air Emissions. International Journal of Life Cycle Assessment, 5(5), 281-6.

Neinhuis, C. and Barthlott, W. (1997). Characterization and Distribution of Water-repellent, Self-cleaning Plant Surfaces. Annals of Botany, 79(6), 667.

Nielsen, S. N. (2007). What has modern ecosystem theory to offer to cleaner production, industrial ecology and society? The views of an ecologist. Journal of Cleaner Production, 15(17), 1639-53.

Nigge, K.-M. (2001a). Generic Spatial Classes for Human Health Impacts, Part I: Methodology. International Journal of Life Cycle Assessment, 6, 1-8.

--- (2001b). Generic Spatial Classes for Human Health Impacts, Part II: Application in an Life Cycle Assessment of Natural Gas Vehicles. International Journal of Life Cycle Assessment, 6(6), 334-8.

Noguerol, L. P., Shikida, C. D. and Monasteria, L. M. (2005). "Seis Centimentros: Uma Analise Antropometrica Da Pof 2002-2003." ANPEC. <http://www.anpec.org.br/encontro2005/artigos/A05A159.pdf>.

Norris, G. A. (2001). Integrating Life Cycle Cost Analysis and LCA. International Journal of Life Cycle Assessment, 6(2), 118-20.

O'Brien, M., Doig, A. and Clift, R. (1996). Social and Environmental Life Cycle Assessment (SELCA). International Journal of Life Cycle Assessment, 1(4), 231-7.

N. R. E. Laboratory. (2002). An Analysis of Hybrid Electric Propulsion Systems for Transit Buses: Milestone Completion Report. By O'Keefe, M. P. and Vertin, K.: U.S. Department of Energy. http://www.nrel.gov/vehiclesandfuels/vsa/pdfs/32858.pdf>.

O'Neill, M. (2003). "WEEE & RoHS and Trends in the Environmental Legislation in European Union." Proceedings of EcoDesign 2003: Third International Symposium on Environmentally Conscious Design and Inverse Manufacturing, Tokyo, Japan, Dec. 8-11. IEEE, Paper No. environmental law, WEEE, RoHS, EU, European Union, 5-8.

Odum, E. P. (1969). The Strategy of Ecosystem Development. Science, 164(3877), 262-70.

--- (1987). Basic Ecology. Philadelphia: Saunders College Publishing.

Odum, H. T. (1995). "Self-organization and maximum empower." In C. A. S. Hall (Ed. Maximum Power: The Ideas and Applications of H.T. Odum (pp. 311-30). Niwot: University Press of Colorado.

D. o. H. a. N. E. Surveys. (2004). Mean Body Weight, Height, and Body Mass Index United States 1960-2002. By Ogden, C. L., Fryar, C. D., Carroll, M. D. and Flegal, K. M.: Center for Disease Control. http://www.cdc.gov/nchs/data/ad/ad347.pdf>.

Okuyama, T. and Holland, J. N. (2008). Network structural properties mediate the stability of mutualistic communities. Ecology Letters, 11, 208-16.

Ometto, A. R., Ramos, P. A. R. and Lombardi, G. (2007). The benefits of a Brazilian agro-industrial symbiosis system and the strategies to make it happen. Journal of Cleaner Production, 15(13-14), 1253-8.

Oner, D. and McCarthy, T. J. (2000). Ultrahydrophobic Surfaces: Effects of Topography Length Scales on Wettability. Langmuir, 16(20), 7777-82.

Ostfeld, R. S. and Keesing, F. (2000). Pulsed resources and community dynamics of consumers in terrestrial ecosystems. Trends in Ecology & Evolution, 15(6), 232-7.

Owens, J. W. (1997). Life-Cycle Assessment - Constraints on Moving from Inventory to Impact Assessment. Journal of Industrial Ecology, 1(1), 37-49.

Panigrahi, B. K. (2008). Bacterial foraging optimisation. Nelder-Mead hybrid algorithm for economic load dispatch, 2(4), 556-65.

--- (2009). Congestion management using adaptive bacterial foraging algorithm. Energy Conversion and Management, 50(5), 1202-9.

Pant, R., Hoof, G. V., Schowanek, D., Feijtel, T. C. J., de Koning, A., Hauschild, M., Pennington, D. W., Olsen, S. I. and Rosenbaum, R. (2004). Comparison between Three Different LCIA Methods for Aquatic Ecotoxicity and a Product Environmental Risk Assessment - Insights from a Detergent Case Study within OMNIITOX. International Journal of Life Cycle Assessment, 9(5), 295-306.

Park, H. S., Rene, E. R., Choi, S. M. and Chiu, A. S. F. (2008). Strategies for sustainable development of industrial park in Ulsan, South Korea - From spontaneous evolution to systematic expansion of industrial symbiosis. Journal of Environmental Management, 87(1), 1-13.

Parker, S. P. (Ed. (1994). McGraw-Hill Dictionary of Scientific and Technical Terms. New York: McGraw-Hill Inc.

Patten, B. C. (1985). Energy cycling in the ecosystem. Ecological Modelling, 28(1-2), 1-71.

Pearce, J. M. (2008). Industrial symbiosis of very large-scale photovoltaic manufacturing. Renewable Energy, 33(5), 1101-8.

Pedersen, K., Emblemsvåg, J., Bailey, R., Allen, J. K. and Mistree, F. (2000). "Validating Design Methods and Research: The Validation Square." Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Baltimore, Maryland, Sept. 10 - 14. American Society of Mechanical Engineers, Paper No. 14579, 12.

Pennington, D. W. (2001). Current Issues in the Characterization of Toxicological Impacts. International Journal of Life Cycle Assessment, 6(2), 89-95.

Pesonen, H.-L., Ekvall, T., Fleischer, G., Huppes, G., Jahn, C., Klos, Z. S., Rebitzer, G., Sonnemann, G. W., Tintinelli, A., Weidema, B. P. and Wenzel, H. (2000).

Framework for Scenario Development in LCA. International Journal of Life Cycle Assessment, 5(1), 21-30.
Petchey, O. and Gaston, K. J. (2002). Extinction and the loss of functional diversity. Proceedings of the Royal Society B, 269, 1721-7.
Peters, G. P. and Hertwich, E. G. (2006). A comment on "Functions, commodities and environmental impacts in an ecological-economic model". Ecological Economics, 59(1), 1-6.
Peyton, K. B. (1998). Fuel Field Manual: Sources and Solutions to Performance Problems. New York: McGraw-Hill.
Pimm, S. L. (1980). Properties of Food Webs. Ecology, 61(2), 219-25.
--- (1984). The complexity and stability of ecosystems. Nature, 307, 321-6.
Pimm, S. L. and Lawton, J. H. (1980). Are Food Webs Divided into Compartments? The Journal of Animal Ecology, 49(3), 879-98.
Pimm, S. L., Lawton, J. H. and Cohen, J. E. (1991). Food web patterns and their consequences. Nature, 350, 669-74.
Pol, T. S. (2006). "Corps et Appartenance sociale: la corpulence en Europe. ." INSEE. <http://www.insee.fr/fr/ffc/docs_ffc/DONSOC06zt.PDF>.
Potting, J. and Hauschild, M. Z. (2006). Spatial Differentiation in Life Cycle Impact Assessment: A decade of method development to increase the environmental realism of LCIA. International Journal of Life Cycle Assessment, 11(1), 11-3.
Potting, J., Schopp, W., Blok, K. and Hauschild, M. (1998). Site-Dependent Life-Cycle Impact Assessment of Acidification. Journal of Industrial Ecology, 2(2), 63-87.
Proc, K., Barnitt, R., Hayes, R. R., Ratcliff, M. and McCormick, R. L. (2006). "100,000-Mile Evaluation of Transit Buses Operated on Biodiesel Blends (B20)." Powertrain and Fluid Systems Conference and Exhibition, Toronto, Canada. Society of Automotive Engineers.
Purvis, A. and Hector, A. (2000). Getting the Measure of Biodiversity. Nature, 405, 212-9.
Rainey, P. B., Buckling, A., Kassen, R. and Travisano, M. (2000). The emergence and maintenance of diversity: insights from experimental bacterial populations. Trends in Ecology & Evolution, 15(6), 243-7.
Raynolds, M., Fraser, R. and Checkel, D. (2000a). The Relative Mass-Energy-Economic (RMEE) Method for System Boundary Selection - Part 1: A Means to Systematically and Quantitatively Select LCA Boundaries. International Journal of Life Cycle Assessment, 5(1), 37-46.
--- (2000b). The Relative Mass-Energy-Economic (RMEE) Method for System Boundary Selection - Part 2: Selecting the Boundary Cut-off Parameter (Z_{RMEE}) and its Relationship to Overall Uncertainty. International Journal of Life Cycle Assessment, 5(2), 96-104.
Reap, J. and Bras, B. (2008). Exploring the Limits to Sustainable Energy Consumption for Organisms and Devices. International Journal of Sustainable Manufacturing, 1(1-2), 78-99.
Reap, J. J., Bras, B., Realff, M. J. and Carmichael, C. (2004). "Using Ecosystem Landsape Models to Investigate Industrial Environmental Impacts." Design

Engineering Technical Conferences and Computers and Information in Engineering Conference, Salt Lake City, Utah USA. ASME.
Reap, J. J., Newcomb, P. J., Carmichael, C. and Bras, B. (2003). "Improving Life Cycle Assessment by Including Spatial, Dynamic and Place-Based Modeling." Design Engineering Technical Conferences and Computers and Information in Engineering Conference, Chicago, Illinois USA. ASME.
Rebitzer, G., Ekvall, T., Frischknecht, R., Hunkeler, D., Norris, G., Rydberg, T., Schmidt, W.-P., Suh, S., Weidema, B. P. and Pennington, D. W. (2004). Life cycle assessment Part 1: Framework, goal and scope definition, inventory analysis, and applications. Environment International, 30, 701-20.
Rebitzer, G. and Hunkeler, D. (2003a). Life Cycle Costing in LCM: Ambitions, Opportunities, and Limitations. International Journal of Life Cycle Assessment, 8(5), 253-6.
Rebitzer, G. and Seuring, S. (2003b). Methodology and Application of Life Cycle Costing. International Journal of Life Cycle Assessment, 8(2), 110-1.
Reed, E. J., Klumb, L., Koobatian, M. and Viney, C. (2009). Biomimicry as a route to new materials. what kinds of lessons are useful?, 367(1893), 1571-85.
Reichmann, O. J. and Seabloom, E. W. (2002). Ecosystem engineering: a trivialized concept? Response. Trends in Ecology & Evolution, 17(7), 308-.
Reynolds, C. (2006). Ecology of Phytoplankton. Cambridge: Cambridge University Press.
Ritzen, S. and Beskow, C. (2001). Actions for integrating environmental aspects into product development. The Journal of Sustainable Product Design, 1, 91-102.
Rooney, N., McCann, K., Gellner, G. and Moore, J. C. (2006). Structural asymmetry and the stability of diverse food webs. Nature, 442, 265-9.
Ross, S. and Evans, D. (2002). Excluding Site-Specific Data from the LCA Inventory: How This Affects Life Cyce Impact Assessment. International Journal of Life Cycle Assessment, 7(3), 141-50.
Rounds, K. S. and Cooper, J. S. (2002). Development of product design requirements using taxonomies of environmental issues. Research in Engineering Design, 13, 94-108.
Ruhland, A., Striegel, G. and Kreisel, G. (2000). Functional Equivalence of Industrial Metal Cleaning Processes - Comparison of Metal Cleaning Process within LCA. International Journal of Life Cycle Assessment, 5(3), 127-33.
Russel, A., Ekvall, T. and Baumann, H. (2005). Life cycle assessment - introduction and overview. Journal of Cleaner Production, 13, 1207-10.
SAE (1999).
Schmitt, O. H. (1938). A Thermionic Trigger. Journal of Scientific Instruments, 15, 24-6.
Schoener, T. H. (1989). Food Webs from the Small to the Large. Ecology, 70(6), 1559-89.
Shiovitz, A. and Craig, E. (1997). "Using data to determine design for environment product goals." Proceedings of the 1997 IEEE International Symposium on Electronics and the Environment San Francisco, CA, USA, May 5-7. IEEE, 105-8.
Simon, H. (2001). The Sciences of the Artificial (3rd ed.). Cambridge: The MIT Press.

Singh, A., Lou, H. H., Yaws, C. L., Hopper, J. R. and Pike, R. W. (2007). Environmental impact assessment of different design schemes of an industrial ecosystem. Resources Conservation and Recycling, 51(2), 294-313.

Smil, V. (2003). Energy at the Crossroads: Global Perspectives and Uncertainties. Cambridge, Massachusetts: MIT Press.

Sole, R. V., Manrubia, S. C., Benton, M. and Bak, P. (1997). Self-similarity of extinction statistics in the fossil record. Nature, 388, 764-7.

Stadler, J., Trefflich, A., Brandl, R. and Klotz, S. (2007). Spontaneous regeneration of dry grasslands on set-aside fields. Biodiversity and Conservation, 16(3), 621-30.

Statzner, B. and Moss, B. (2004). Linking ecological function, biodiversity and habitat: a mini-review focusing on older ecological literature. Basic Applied Ecology, 5(2), 97-106.

Strauss, A. L. and Corbin, J. (1994). "Grounded Theory Methodology: An Overview." In N. K. Denzin and Y. S. Lincoln (Eds.), Handbook of Qualitative Research. London: SAGE Publications.

--- (1998). Basics of Qualitative Research: Techniques and Procedures for Developing Grounded Theory (2nd ed.). Thousand Oaks: Sage Publications, Inc.

Suh, S. (2004). Functions, commodities and environmental impacts in an ecological-economic model. Ecological Economics, 48(4), 451-67.

--- (2006). Reply: Downstream cut-offs in integrated hybrid life-cycle assessment. Ecological Economics, 59(1), 7-12.

Suh, S. and Huppes, G. (2005). Methods for Life Cycle Inventory of a product. Journal of Cleaner Production, 13(7), 687-97.

Suh, S., Lenzen, M., Treloar, G. J., Hondo, H., Horvath, A., Huppes, G., Jolliet, O., Klann, U., Krewitt, W., Moriguchi, Y., Munksgaard, J. and Norris, G. (2004). System Boundary Selection in Life-Cycle Inventories Using Hybrid Approaches. Environmental Science & Technology, 38(3), 657-64.

Sumper, M. and Kroger, N. (2004). Silica formation in diatoms: the function of long-chain polyamines and silaffins. Journal of Materials Chemistry, 14, 2059-65.

Szczerbicki, E. and Drinkwater, M. (2004). Concurrent Engineering Design for Environment. Cybernetics and Systems, 35, 667-81.

Tian, Y., Pesika, N., Zeng, H., Rosenburg, K., Zhao, B., McGuiggan, P., Autumn, K. and Israelachvili, J. (2006). Adhesion and friction in gecko toe attachment and detachment. Proceedings of the National Academy of Sciencies, 103(51), 19320-5.

Tillman, A.-M., Ekvall, T., Baumann, H. and Rydberg, T. (1994). Choice of system boundaries in life cycle assessment. Journal of Cleaner Production, 2(1), 21-9.

Tilman, D., Reich, P. B. and Knops, J. M. H. (2006). Biodiversity and ecosystem stability in a decade-long grassland experiment. Nature, 441, 629-32.

Toko, K. (2000). Biomimetic Sensor Technology. Cambridge: Cambridge University Press.

Tolle, D. A. (1996). Regional Scaling and Normalization in LCIA: Development and Application of Methods. International Journal of Life Cycle Assessment, 2(4), 197-208.

Turner, M. G., Gardner, R. H. and O'Neill, R. V. (2001). Landscape Ecology in Theory and Practice: Pattern and Process. New York: Springer-Verlag.
Turner, R. K., Pearce, D. and Bateman, I. (1993). Environmental economics: an elementary introduction. Baltimore: Johns Hopkins University Press.
Udo de Haes, H. A. (2006). How to approach land use in LCIA or, how to avoid the Cinderella effect? Comments on 'Key Elements in a Framework for Land Use Impact Assessment Within LCA'. International Journal of Life Cycle Assessment, 11(4), 219-21.
Udo de Haes, H. A., Finnveden, G., Goedkoop, M., Hauschild, M., Hertwich, E. G., Hofstetter, P., Jolliet, O., Klopffer, W., Krewitt, W., Lindeijer, E., Muller-Wenk, R., Olsen, S. I., Pennington, D. W., Potting, J. and Steen, B. (Eds.). (2002). Life-Cycle Impact Assessment: Striving towards Best Practice. Pensacola: Society of Environmental Toxicology and Chemistry.
Udo de Haes, H. A., Jolliet, O., Finnveden, G., Hauschild, M., Krewitt, W. and Muller-Wenk, R. (1999). Best Available Practice Regarding Impact Categories and Category Indicators in Life Cycle Impact Assessment. International Journal of Life Cycle Assessment, 4(2), 66-74.
Ulanowicz, R. E. (1983). Identifying the structure of cycling in ecosystems. Mathematics and Bioscience, 65(219-237).
--- (1996a). "Trophic Flow Networks as Indicators of Ecosystem Stress." In G. A. Polis and K. O. Winemiller (Eds.), Food Webs Integration of Patterns & Dynamics. New York: Chapman & Hall.
--- (1996b). "Trophic Flow Networks as Indicators of Ecosystem Stress." In G. A. Polis and K. O. Winemiller (Eds.), Food Webs: Integration of Patterns & Dynamics. New York: Chapman & Hall.
Ulanowicz, R. E. and Abarca-Arenas, L. G. (1997). An informational synthesis of ecosystem structure and function. Ecological Modeling, 95, 1-10.
UNEP (2003). "Evaluation of Environmental Impacts in Life Cycle Assessment." United Nations Environment Programme, Division of Technology, Industry and Economics (DTIE), Production and Consumption Unit, Paris.
Urry, D. W., Xu, J., Wang, W., Hayes, L., Prochazka, F. and Parker, T. M. (2003). "Development of Elastic Protein-Based Polymers as Materials for Acoustic Absorption." Symposium on Materials Inspired by Biology, San Francisco, California. Materials Research Society, 81-92.
van Beers, D., Corder, G., Bossilkov, A. and van Berkel, R. (2007). Industrial symbiosis in the Australian minerals industry - The cases of Kwinana and Gladstone. Journal of Industrial Ecology, 11(1), 55-72.
Vermeij, G. J. (2004). Nature an Economic History. Princeton: Princeton University Press.
--- (2006). Historical Contingency and the Purported Uniqueness of Evolutionary Innovations. Proceedings of the National Academy of Sciencies, 103(6), 1804-9.
Vignerova, J., Bradec, M. and Blaha, P. (2006). Two centuries of growth among Czech children and youth. Economics & Human Biology, 4(2), 237-52.
Vigon, B. W. and Jensen, A. A. (1995). Life Cycle Assessment: Data Quality and Databases Practitioner Survey. Journal of Cleaner Production, 3(3), 135-41.

Vogel, S. (1998). Cats' Paws and Catapults: Mechanical Worlds of Nature and People. New York: W. W. Norton and Company, Inc.
Vojtova, L., Turro, N. J. and Koberstein, J. T. (2003). "ATRP Synthesis and Characterization of α,ω-allyl-Terminated Macromonomers as Precursors for End-Linked Gels and Hydrogels." Symposium on Materials Inspired by Biology, San Francisco, California. Materials Research Society, 59-73.
Wackernagel, M. and Rees, W. (1996). Our Ecological Footprint: Reducing Human Impact on the Earth. Gabriola Island: New Society Publishers.
Wagner, T., Neinhuis, C. and Barthlott, W. (1996a). Contaminability of Insect Wings as a Function of Their Surface Sculptures." Acto Zoologica, 76, 213-25.
--- (1996b). Wettability and Contaminability of Insect Wings as a Function of Their Surface Sculptures. Acta Zoologica, 76, 213-25.
Waldron, K. J. (2000). "A Brief History of Biomimetic Robotics." International Symposium on History of Machines and Mechanisms, Cassino, Italy (M. Ceccarelli, Ed.). Kluwar Academic Publishers, 371-8.
Warren, P. H. (1990). Variation in Food Web Structure: The Determinants of Connectance. The American Naturalist, 136(5), 689-98.
Watt, K. E. F. (1973). Principles of Environmental Science. New York: McGraw-Hill, Inc.
Wayne, W. S., Clark, N. N., Nine, R. D. and Elefante, D. (2004). A Comparison of Emissions and Fuel Economy from Hybrid-Electric and Conventional-Drive Transit Buses. Energy & Fuels, 18, 257-70.
Webb, B. and Consi, T. R. (Eds.). (2001). Biorobotics: Methods and Applications. Menlo Park: AAAI Press.
Weber, M. and Borcherding, K. (1993). Behavioral influences on weight judgments in multiattribute decision making. European Journal of Operations Research, 67(1), 1-12.
Weidema, B. (2001). Avoiding Co-Product Allocation in Life-Cycle Assessment
Journal of Industrial Ecology, 4(3), 11-33.
Wenzel, R. N. (1936). Resistance of Solid Surfaces to Wetting by Water. Industrial and Engineering Chemistry, 28(8), 988-94.
Whittaker, R. J. and Fernandez-Palacios, J. (2007). Island Biogeography: Ecology, Evolution and Conservation (2nd ed.). Oxford: Oxford University Press.
WHO "Global Database on Body Mass Index." World Health Organization. http://www.who.int/bmi/index.jsp
Wilson, J. O. (2008). A systematic approach to bio-inspired conceptual design. doctoral thesis, Georgia Institute of Technology.
Woodward, G., Ebenman, B., Emmerson, M., Montoya, J. M., Olesen, J. M., Valido, A. and Warren, P. H. (2005). Body size in ecological networks. Trends in Ecology & Evolution, 20(7), 402-9.
Worm, B., Barbier, E. B., Beaumont, N., Duffy, J. E., Folke, C., Halpern, B. S., Jackson, J. B. C., Lotze, H. K., Micheli, F., Palumbi, S. R., Sala, E., Selkoe, K. A., Stachowicz, J. J. and Watson, R. (2006). Impacts of Biodiversity Loss on Ocean Ecosystem Services. Science, 314, 787-90.

Xiu, Y., Zhu, L., Hess, D. W. and Wong, C. P. (2006). Biomimetic Creation of Hierarchical Surface Structures by Combining Colloidal Self-Assembly and Au Sputter Deposition. Langmuir, 22, 9676-81.

Yang, S. L. and Feng, N. P. (2008). Case study of industrial symbiosis: Nanning Sugar Co., Ltd. in China. Resources Conservation and Recycling, 52(5), 813-20.

ZERI (2004). "Beer: Making Bread and Mushrooms." Zero Emissions Research and Initiatives. Dec. 10

Zhang, X. P., Stromman, A. H., Solli, C. and Hertwich, E. G. (2008). Model-centered approach to early planning and design of an eco-industrial park around an oil refinery. Environmental Science & Technology, 42(13), 4958-63.

Zhu, L., Xu, J., Zhang, Z., Hess, D. W. and Wong, C. P. (2005). "Lotus Effect Surface for Prevention of Microelectromechanical System (MEMS) Stiction." Electronics Components and Technology Conference. IEEE, 1798-801.

Zhu, Q. and Cote, R. P. (2004). Integrating green supply chain management into an embryonic eco-industrial development: a case study of the Guitang Group. Journal of Cleaner Production, 12(8-10), 1025-35.

Zhu, Q. H., Lowe, E. A., Wei, Y. A. and Barnes, D. (2007). Industrial symbiosis in China - A case study of the Guitang Group. Journal of Industrial Ecology, 11(1), 31-42.