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A DESIGN FRAMEWORK FOR SUSTAINABLE INFRASTRUCTURE

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A DESIGN FRAMEWORK FOR SUSTAINABLE INFRASTRUCTURE

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ABSTRACT

Aristotle theorized, "The whole is more than the sum of its parts." Design engineers often overlook this simple philosophy. We employ a reductionist approach when designing the built environment: engineering solutions for the individual parts rather than the system as a whole, creating and exacerbating problems in the process. A whole system, interdisciplinary approach that considers the interrelatedness of global issues is increasingly recognized as essential to finding truly sustainable engineering solutions (NSB, 2007). However, both the precise nature of this whole systems approach, and the best ways to incorporate it in engineering education remain undefined. To address this gap in knowledge, this research: (1) methodically reviewed the literature to define and unify the general principles of whole systems design; and (2) used the literature to develop a conceptual framework for whole systems design for sustainable infrastructure.

A systematic literature review guided by a predefined protocol used 13 search terms spanning the engineering, architecture, and planning disciplines to identify components of the whole systems framework. Sources identified in the literature review fell under five primary categories: sustainable development; architecture, planning, and urban design; engineering, environmental management and business; and systems thinking. Principles were extracted from the resources, empirically coded, and organized into a framework using concept mapping. The resulting framework was organized into three overarching categories: design processes, design principles, and design methods, with a total of 20 principles, or components of whole systems design. It combines the theories, perspectives, and practices of multiple design disciplines and experts making it germane for applications of design ranging from the microscopic level of a chemical, to the macroscopic level of a

city, for example. Organizing the literature surrounding whole systems design aids in building consensus around the defining elements and sets the stage for future research on the subject.

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CHAPTER ONE: INTRODUCTION

"To develop a complete mind, study the science of art, study the art of science. Learn how to see. Realize that everything connects to everything else."

- Leonardo Da Vinci

We have gotten away from Leonardo's advice. For example, engineering "designers" can graduate and practice without having ever taken a class in art or philosophy, or even in seemingly closely related fields like architecture. The engineering curriculum has become so burdened with technical and discipline specific courses that the opportunity for engineers to develop creative and alternative perspectives has virtually disappeared. Yet to create solutions to the complex problems found in the real world, designers must bring creativity and emotional intelligence in addition to technical expertise. Designers will have little choice but to heed Leonardo's advice and adopt more holistic approaches to design. In this chapter the context of these problems is introduced as well as the scope of the research designed to help address them.

1.1. Context

1.1.1. Defining Sustainability and Sustainable Design

The most widely cited definition of sustainability comes from the 1987 Brundtland Commission, which states that sustainability "meets the needs of the present without compromising the ability of future generations to meet their own needs," (Brundtland, 1987). The all-encompassing nature of this definition is a source of both unanimity and controversy. To refine the broadness of the Brundtland definition, consider the National Park Service's observation that, "Sustainability does not require a loss in the quality of life, but does require a change in mind-set, a change in values toward less consumptive lifestyles. These changes must embrace global interdependence, environmental stewardship, social responsibility, and economic viability" (National Park Service, 1993). The National Park Services goes on to prescribe that "Sustainable design must use an alternative approach to traditional design that incorporates these changes in mind-set. The new design approach must recognize the impacts of every design choice on the natural and cultural resources of the local, regional, and global environments" (National Park Service, 1993). Thus the definition of sustainable design that guides this research is:

> Sustainable design is an alternative approach to traditional design which leads toward a less consumptive mindset that embraces global interdependence, environmental stewardship, social responsibility, and economic viability, and considers the impacts of design choices at local, regional, and global levels.

1.1.2. Why Do We Need Sustainable Design?

The problems we face as designers, and as a society are indisputably significant. Shortages of energy, natural resources, water, and food; threats of war, and political instability; rising levels of poverty, homelessness, and disease; slipping quality of education and infrastructure; all of these things are compounded by what is arguably our largest issue, radical population growth. The current world population sits at around 7 billion people, and in a recently revised projection by the UN is said to reach 10.1billion by 2100, and continue to grow (Kaiser, 2011). Rapid population expansion accelerates the strain on natural resources and energy and ultimately magnifies the impact humans have on the health of the planet. Carbon footprint measures the impact human activities have on the environment, by equating to the amount of greenhouse gases produced in our daily lives through burning fossil fuels for electricity, heating, and transportation, etc. to a unit of metric tons of carbon (Carbon Footprint, n.d.). This environmental impact measure is associated particularly with the environmental issue of climate change, which theorizes the higher the carbon footprint, the larger the impact on global climate change.

The average American has a carbon footprint of 20 metric tons of CO2 each year, approximately five times the annual world average of 4 metric tons of CO2 per person (a figure that includes the US population) (Massachusetts Institute of Technology [MIT], 2008). With a carbon footprint estimated at 8.5 metric tons of CO2, the U.S. homeless person is still more than twice as demanding as the world average (MIT, 2008). Consider for a moment, the worldwide target to combat climate change is 2 metric tons (Carbon Footprint, n.d.). Given these numbers, it has hopefully become apparent that the current distribution of resource and carbon intensity is anything but equitable. But carbon emissions and climate change are just one piece of the sustainability pie, and a highly debated slice at that; we face a multitude of other undeniable social, economic, and ecological issues mentioned earlier. Something will have to give; the planet simply cannot support this current trajectory of intense resource use partnered with exploding global population. For their efforts not to be proven futile, engineers, designers, and policy makers will need to rise to these challenges with radically creative solutions, and they must do so under the constraints of social, economic, and environmental sustainability.

These global issues are further complicated by a growing urbanization trend. The complex nature of cities, their infrastructure, and their development patterns will be a strong focus of engineering and design efforts in the future. Over half the world’s population of nearly 7 billion people currently resides in cities or urban areas, and those numbers are projected to grow substantially over the next few decades (UNFPA, 2007). These rapidly growing urban centers strain social, economic, and natural resources. The urban population is responsible for nearly 75 percent of the world's energy consumption, while representing only 2 percent of the world's surface area (Oliver, 2007). This density and concentration of resource usage is not necessarily a bad thing; the smaller geographic footprint is an opportunity for urban designers and engineers to thoughtfully and intelligently improve resource distribution efficiency, reduce transportation costs, and reduce the overall impact on the environment.

But the direction urban settlement patterns are trending towards is anything but a desirable density with a minimal geographic footprint. In the 20-year period from 1970 to 1990, the 100 largest urbanized areas in the United States sprawled an additional 14,545 square miles consuming more than 9 million acres of natural habitats, farmland, and rural space (NumbersUSA, n.d.). The trend of sprawling development and population growth is debated as the source of many social, environmental, and economic maladies.

The Carrying Capacity Network suggests that if current population growth trends continue, the USA will cease to be able to export food by about the year 2030, thus losing approximately $40 billion in annual income from export sales. Growing distances between where people live, work, and play leads to increased dependence on the personal automobile and has in turn been suggested to lead to amplified social isolation and obesity. Increasing cases of asthma, climate change, erosion, extinction of wildlife, and the gobbling up of small farms are just a few plights of this unsustainable land use pattern (Nasser & Overberg, 2001). Growing populations and spreading development are increasing the demand for resources such as energy and water while making efficient distribution more difficult. The complex beast known as urban sprawl is just one of many issues related to infrastructure and the built environment that urban designers, engineers, and policy makers will have to face sooner rather than later.

When we look to the developing world though, the matters are even graver. Three in every four people living on less than a dollar a day, also suffering from malnutrition, reside in rural areas in developing countries. However, urbanization does not equate to improvements in their quality of life. Urban slum growth is overtaking urban growth by a wide margin (United Nations Development Program [UNDP], 2007). In fact, the United Nations reported that “in 2005, one out of three urban dwellers (approximately 1 billion people) was living in slum conditions” (UN, 2007). Basic needs such as shelter, food, energy, and water are a daily struggle for people in third world nations across the globe. Access to modern energy is a concern in these developing countries where “some 2.5 billion people are forced to rely on biomass—fuel wood, charcoal and animal dung—to meet their energy needs for cooking. In sub-Saharan Africa, over 80 percent of the population depends on traditional biomass for cooking, as do over half of the populations of India and China” (UNDP, 2007).

Water also remains a great issue: 90 percent of urban sewage in the developing world is discharged into rivers, lakes, and coastal waterways without any treatment. Nearly 220 million urban residents in the developing world lack a source of safe drinking water near their homes (DEPweb, n.d.). The challenges plaguing the developing world also extend to social infrastructure like education: based on enrollment data, approximately 72 million children of primary school age in the developing world were not in school in 2005. Of those 72 million children, 57 percent of them were girls (UN, 2007). Engineers, policy makers, and designers must help develop these impoverished nations in a sustainable manner to provide people with greater quality of life that respects social needs, makes economic sense, and restores environmental health.

Shifting perspectives from global to more local issues, in the United States designers and engineers are facing serious challenges with regards to aging and failing infrastructure, further constrained by exceedingly insufficient budgets. The American Society of Civil Engineers (ASCE) issues a report card every two years assessing the health of the country's infrastructure and the 5-year capital investment needed to improve the infrastructure grades. ASCE released its first report in 1988 evaluating eight infrastructure categories, and assigned an overall grade of C to U.S. infrastructure (ASCE, 2009). The latest report card evaluating the nation's infrastructure across fifteen categories in 2009 gave America's overall infrastructure a D and recommended an investment of $2.2 Trillion to begin to improve this dismal score (ASCE, 2009). At the head of the class, the solid waste category, received the highest grade of a C+ (ASCE, 2009). The dismal "students" which included the drinking water, inland waterways, levees, roads, and wastewater infrastructure categories received the lowest grades of D- (ASCE, 2009). At least nobody got an F right? Infrastructure receiving that grade would be virtually unusable.

Rising to these local and global challenges will require a drastic change in the way we design our world. We can no longer ignore the interrelatedness of the systems in our world. These issues are intertwined, and the solutions designers and engineers dream up will have to recognize and consider that fact. For example, consider an engineer interested in alleviating congestion on a road in a city. Under guidance of traditional design theory, they would normally consider adding additional travel lanes, or constructing a new street through an existing neighborhood. However, this shortsighted approach has historically been shown to be ineffective and often the measure has the opposite effect of its original intent. What typically happens when we add a new lane of traffic or build a new road is automobile traffic will actually increase and traffic conditions further deteriorate. Also, more often than not, designing and building new streets for automobiles destroys neighborhoods, hurts local businesses, and leads to additional pollution, runoff, and other adverse environmental impacts. A more holistic approach to the problem would consider ways to reduce the number of personal automobiles on the road perhaps by adding mass transit, bike lanes, and reducing travel lane width, in turn making the street more pedestrian friendly. These complete street measures have been shown to reduce or handle current traffic patterns, while improving the safety, walkability, and economic vitality of neighborhoods. As this example illustrates, we will have to break down silos, work across disciplines, change our perspectives, and get creative. Most of these ideas aren't new; designers in every field have been talking about them for years. However, the time has come to do more than just talk amongst ourselves; the time to share our ideas and act on them is here, and some could even argue that it has passed.

1.2. Problem Statement

Designing the systems that make up the urban fabric optimally and collaboratively will be the key to ensuring environmental, economic, and social sustainability. Whole systems design is one approach to sustainable design offering great potential, however the principles guiding the whole systems approach are not clearly defined or understood by academia and practicing designers (Charnley et al, 2010; NSB, 2007). The field of whole systems design is still young, and the literature surrounding it remains limited (Coley, 2009). This ambiguity leads to difficulty in implementing the whole systems design process (Charnley et al, 2010). Design itself is difficult to form consensus about, it's definition, principles, and optimal process are open to multiple interpretations. Highlighting commonalities and considering multiple perspectives of sustainable design theory can build consensus and demonstrate that the design disciplines are largely arguing over semantics. However, observing differences in design theory amongst these disciplines can also fill in missing pieces to develop a more holistic design philosophy.

The authors of principles of green engineering stated that "When dealing with design architecture—whether it is the molecular architecture required to construct chemical compounds, product architecture to create an automobile, or urban architecture to build a city—the same green engineering principles must be applicable, effective, and appropriate." However, the principles of green engineering, initiated by chemical engineers, seem to emphasize or favor the molecular scale. The Rocky Mountain Institute has developed Factor Ten, or 10xE Principles that embody whole systems thinking and integrated design. While these principles appear to have more broad applicability than the principles of green engineering, they are heavily focused on energy. This research is not a direct response to either the principles of green engineering or the 10xE principles, but rather it seeks to address the narrow foci and find common ground among the design disciplines to develop a more complete and applicable framework for design.

A previous research study (Charnley et al, 2010) explored the process of whole systems design and identified factors that influenced its success. A key factor that was identified to significantly impact the success of whole systems design in the study was “understanding of purpose and process.” The researchers concluded from their analysis of multiple case studies that:

> “The principles of whole system design are frequently misunderstood or unknown and therefore it should not be assumed that all actors have a shared understanding of the process required to reach a whole system solution.”

In fact, researchers had difficulty finding literature surrounding whole systems design and in their background section and didn’t attempt to identify the guiding principles of whole systems design, but rather focused on factors influencing the process. A participant in the study highlighted the ambiguity surrounding whole systems design, stating that the process of whole system design is new to everyone and therefore still needs exploring (Charnley, Lemon, & Evans, 2010). He specifically said:

> “At the moment we are not very good at it (whole system design) and we haven’t had much practice; no one has. We haven’t had very long to work out how to put whole system design teams together at all” (Charnley, Lemon, & Evans, 2010).

The limited literature discussing whole systems design demonstrates a need to better define and develop this design paradigm. This research addresses this issue by expanding the boundaries of the literature to incorporate other more widely accepted and known principles of sustainable development, engineering, and design. In this way, this research aims to highlight commonalities to build consensus and illuminate differences to fill in gaps and build a framework that can help designers meet the challenges of sustainable design.

1.3. Scope

The sustainable design field is broad, therefore early on in the research process a definition of whole systems design was needed to help guide (but not narrowly bind) the research process. The Rocky Mountain Institute (RMI) defines whole systems design accordingly:

> *"Whole-system designers* optimize the performance of buildings, vehicles, machines, and processes by collaborating in diverse teams to understand how the parts work together as a system, then turning those links into synergies. *Integrative design* optimizes an entire system as a whole, rather than its parts in isolation. This can solve many problems at once, create multiple benefits from single expenditures, and yield more diverse and widely distributed benefits that help attract broader support for implementation" (RMI, 2010).

For the purposes of this study, a definition for whole systems design has been adapted to broaden its applicability in many design disciplines:

> "Whole systems design considers an entire system as a whole from multiple perspectives to understand how it's parts can work together as a system to create synergies and solve multiple design problems simultaneously. It is an interdisciplinary, collaborative, and iterative process."

The above definition was used only to guide the study, however the purpose of this study was to better define and develop a framework of whole systems. Over the course of the study, the definition is further developed and refined based upon the literature.

This research did not focus its attention on defining or mapping the process of whole systems design. Previous studies have been conducted that examine the factors influencing the process of whole systems design and researchers have found that whole systems design was not truly understood nor well defined. Thus this research concentrated on defining principles or elements of whole systems design. However, principles or elements that describe the process of whole systems design and the methods used in whole systems design were considered. Defining whole systems design is the necessary first step for the future study of the whole systems design process itself.

1.4. Research Questions

This research aims to answer the following questions:

1. What are the guiding principles of sustainable design as defined by engineering and related design disciplines (e.g. architecture, planning)?
2. How can these individual principles be integrated into a holistic set of design principles, termed whole systems design, that is applicable for sustainable design across all disciplines?

Answering these research questions will define the principles of whole systems design from the perspective of multiple design disciplines, in turn improving the process of whole systems design. Enhancing the whole systems design process could lead to more sustainable design solutions to the interconnected worldwide challenges we face.

1.5. Research Objective

The objective of this research is to discover and organize the design framework that defines sustainable whole systems design. Emerson said “As to methods there may be a million and then some, but principles are few. The man who grasps principles can successfully select his own methods. The man who tries methods, ignoring principles, is sure to have trouble.” Webster’s dictionary defines a principle as “a comprehensive and fundamental law, doctrine, or assumption; a rule or code of conduct.” Discovering general principles, processes, and methods of whole systems design and identifying effective methods to incorporate these principles into engineering education will help students postulate solutions for more sustainable infrastructure design. Defining whole systems design and the principles guiding it is an essential step to advancing the use of the process by designers. The research will help current and future designers produce solutions that efficiently address the ecological, social, and economic demands of the system as a whole, a key to building sustainable communities and cities of the future.

1.6. Research Steps

To achieve the research objective the following steps were taken:

- **Identify principles of whole systems design through a systematic literature review.** The planning phase of the systematic review requires the identification of the need for the review and the development of a literature review protocol. During the review process, relevant sources were identified from journal articles, published books, and Internet sources and the quality of the studies were assessed.
- **Organize principles of whole systems design with concept mapping techniques.** Then the theories, principles, and elements of sustainable design conducted by engineers, architects, planners, and urban designers were extracted and synthesized into a holistic set of design principles, processes, and methods that define whole systems design for sustainability. Concept mapping techniques were used to organize the principles into a coherent framework.
- **Report implications, limitations, and conclusions of the review.** The findings of this research provide valuable knowledge for both members of academia and

practicing design professionals. Clarifying the implications, limitations, and conclusions for future applications of the design principles identified by this research is an essential step in the research process.

- **Identify areas for future research.** This research unifies the foundational principles of a broadly applicable design paradigm, whole systems design that can result in more effective sustainable solutions. However, it also sets the stage for future research opportunities in the field of whole systems design.

1.7. Thesis Structure

This study identified and unified the principles of sustainable design paradigms into a holistic design approach, whole systems design, through a systematic review and analysis of the literature. To achieve these aims, a thorough search of the literature surrounding sustainable design in multiple design disciplines was conducted to identify principles of whole systems design. These sources were analyzed, coded, sorted into themes, and ultimately unified under a framework to define the guiding principles of whole systems design. Chapter Two details the systematic methods used to conduct the literature search, as well as analyze, code, and organize the design principles into a unified whole systems design framework.

The results of the literature review in Chapter Three provides evidence that multiple design disciplines and sustainable design paradigms share common principles and fundamental rules that guide the designer towards more sustainable solutions. However, the literature also demonstrates that while these disciplines share some key ideas, they rarely transcend disciplinary boundaries and continue to isolate their design initiatives. Chapter Three also shows the framework for whole systems design and an analysis of the resources identified in the literature review, including an analysis of the disciplines and design paradigms considered. The final chapter, Chapter Four, identifies future research opportunities for developing a strategic process model for whole systems design of sustainable cities and green infrastructures, as well as for outreach and dissemination of the principles into both industry and engineering education.

CHAPTER TWO: RESEARCH METHODS

"Merit, however inconsiderable, should be sought for and rewarded. Methods are the master of masters."

-Charles Maurice de Talleyrand

This chapter elaborates on the research approach used to identify the principles and organize the defining framework of whole systems design. A systematic literature review based on the combined methods of three types of systematic reviews was used to identify the principles of whole systems design and concept mapping was used to organize the framework.

2.1. Approach

A systematic literature review identifies, evaluates, and interprets all available "research relevant to a particular research question or topic area" (Kitchenham, 2004). The primary reasons for conducting a systematic literature review are to:

1. Summarize the existing literature around a subject,
2. Identify gaps in current research and suggest future research, and
3. Provide a framework or background to position future research.

This research was focused primarily on the third reason for conducting a literature review: providing a framework or background to position future research on whole systems design. Systematic reviews synthesize research on a subject in a manner that is viewed as fair because they use a predefined search strategy that is well documented and repeatable (Kitchenham, 2004).

Keele University in the UK developed procedures for performing systematic reviews for software engineers. While this particular research is not based in software engineering, this research has similar needs and therefore the framework has been adapted to accommodate the qualitative nature of this engineering research. The researchers at Keele pointed out that “software engineering has relatively little empirical research compared with the large quantities of research available on medical issues, and research methods used by software engineers are not as rigorous as those used by medical researchers” (Kitchenham, 2004). The method developed at Keele would be most appropriate for this research because the literature is similarly limited and the methods used in the field are not as rigorous. The method developed at Keele University is based on the three most well known types of systematic literature reviews that are generally used in medical research: the Australian National Health and Medical Research Council, The Cochrane Reviewers Handbook, and the CRD Guidance.

The process outlined by the Australian National Health and Medical Research Council consists of: (1) question formulation, (2) finding studies, (3) appraisal and selection of studies, (4) summary and synthesis of relevant studies, and (5) determining the applicability of the results (Kitchenham, 2004; National Health & Medical Research Council [NHMRC], 2000). The Cochrane Reviewers Handbook outlines a more detailed process involving: (1) developing a protocol, (2) formulating the problem, (3) locating and selecting studies for reviews, (4) assessment of study quality, (5) collecting data, (6) analyzing and presenting results, and (7) interpreting the results (Kitchenham, 2004; Higgins & Green, 2011). The method developed at Keele University most closely aligns with the steps outlined by the CRD Guidance method. According to CRD Guidance, researchers: (1) identify the need for a review and prepare a proposal for a systematic review, (2) develop a review protocol, (3) identify research and select studies, (4) assess the study quality, (5) extract data and monitor progress, (6) synthesize the data, and finally (5) report and make recommendations (Kitchenham, 2004; Khan et al, 2001).

2.2. Methods

As adapted from the Keele University review method, there were three primary stages of the literature review: (1) planning the review, (2) conducting the review, and (3) reporting the review as shown in Figure **1** (Kitchenham, 2004).

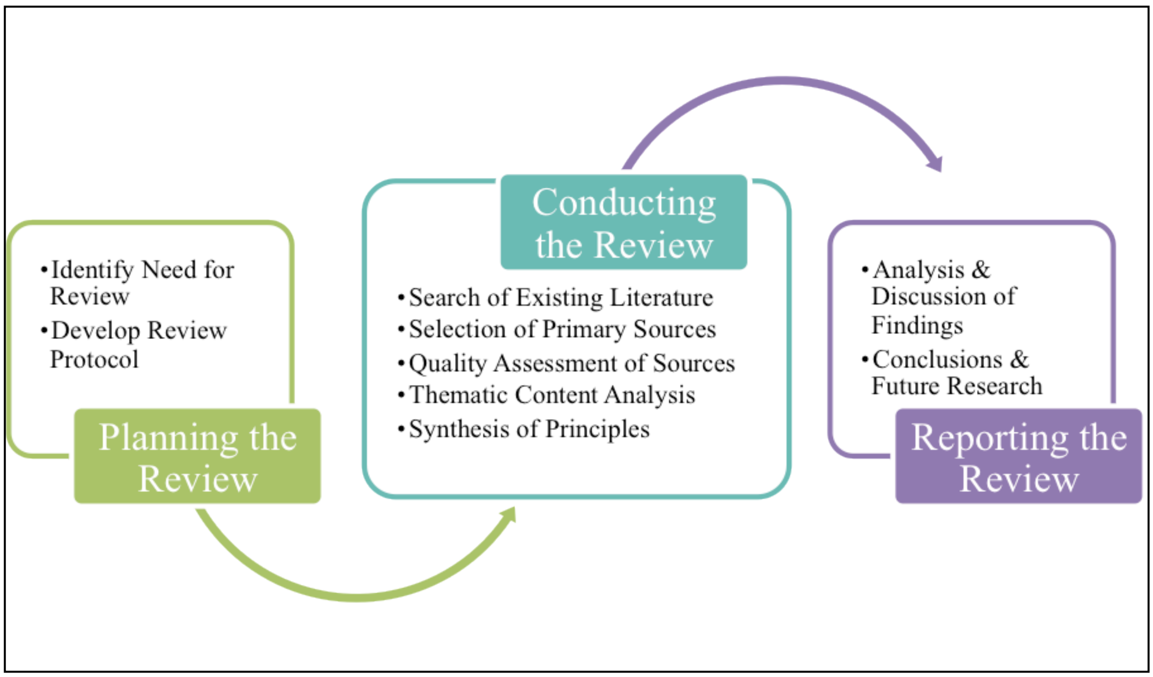

Figure 1: Literature Review Process

2.2.1. Planning the Review

In the planning phase of the systematic literature review, the need was identified and a review protocol was developed that outlined: the rationale for the review, the research questions, search strategy, selection criteria and procedures, quality assessment procedures, data extraction strategy, data synthesis methods, and the project timetable. A total of 13 search terms spanning the engineering, architecture, and planning disciplines were used, ranging from "whole systems design principles" to "sustainable design principles" to "sustainable urbanism principles." Sources identified in the literature review fell under five primary categories: sustainable development; architecture, planning, and urban design; engineering, environmental management and business; and systems thinking (Figure 2).

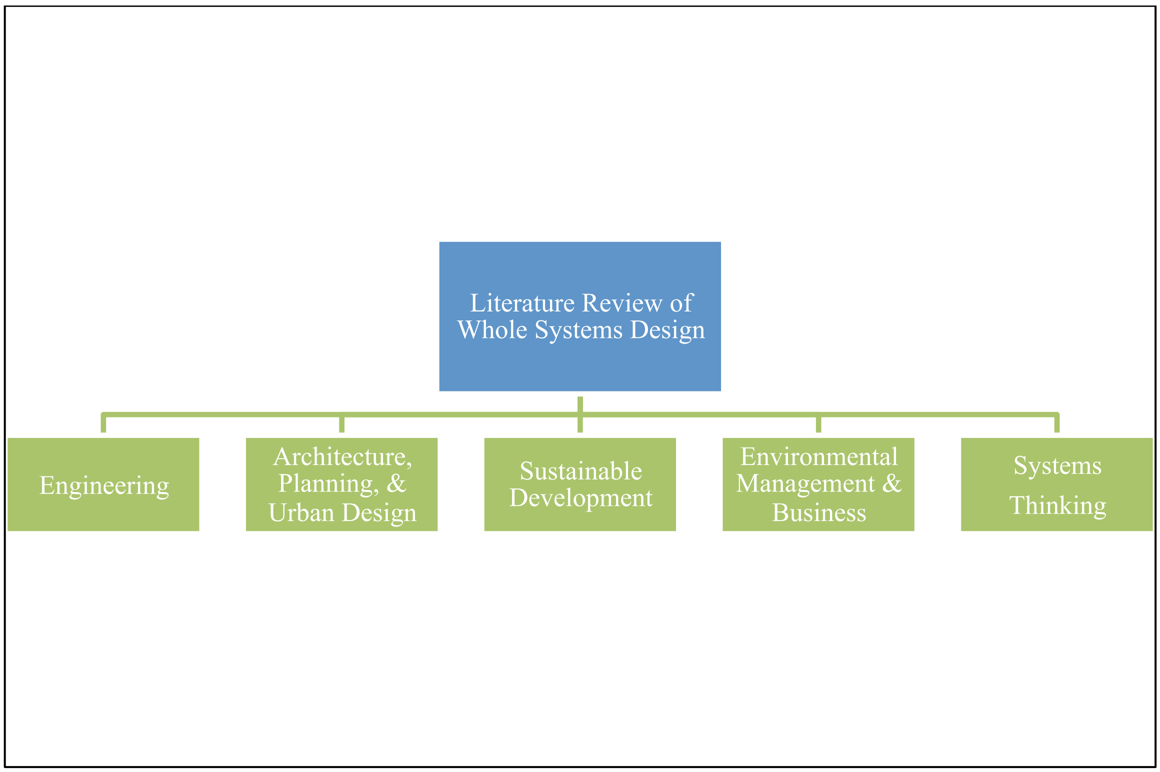

Figure 2: Categories of Sources for Literature Review

2.2.2. Conducting the Review

Resources were identified beginning with databases (Google Scholar and Science Direct) and followed up with reference lists from relevant articles, books, and reports. To reasonably bound the search efforts, a time frame of 1987 through 2011 was used. 1987 was the year that the Brundtland report was issued and the term sustainability as defined for the purposes of this research came into existence. The complete list of search terms used in the Google Scholar and Science Direct databases was:

- Whole systems design principles
- Whole systems thinking principles
- Whole systems approach
- Sustainable design principles
- Green design principles
- Ecological design (Eco-Design) principles
- Integrated design principles
- Cradle to cradle design principles
- Sustainable development principles
- Sustainable engineering principles
- Green engineering principles
- Design for the environment principles
- Biomimicry principles

The word "principles" was added to each of the search terms to narrow the results to a reasonable number and to help find sources that specifically dealt with principles and frameworks of design. The search process was documented electronically in an excel worksheet similar to the table shown in

Table **1**.

Table 1: Documentation of Search Process

		Google Scholar		Science Direct
Date	**Search Term**	**Search Specs**	**# Of Results**	**# Of Results**

		Google Scholar		Science Direct
Date	**Search Term**	**Search Specs**	**# Of Results**	**# Of Results**
1/5/11	whole system design	(Yr. 1987-2011, exact phrase, added the word principles)	268	69
1/6/11	whole systems thinking principles			16
1/9/11	"sustainable design" and "principles"			363
1/9/11	"green design" principles			302
1/10/11	"ecological engineering" principles			246
1/10/11	"cradle to cradle" principles			143
1/10/11	"green engineering" principles			219
1/10/11	"integrative design" principles			42
1/10/11	"integrated design" for sustainability			232
1/10/11	"biomimicry" principles			221
1/10/11	"sustainable development principles"			275
1/13/11	"sustainable engineering" principles			82
1/13/11	"design for the environment" principles			252
1/14/11	"whole system approach" design			179
1/17/11	"whole systems thinking" principles	(Yr. 1987-2011, bio, chem, engin, social)	233	
1/17/11	"whole systems approach" to sustainable design	(Yr. 1987-2011, bio, chem, engin, social)	349	
1/17/11	"sustainable design principles"	(Yr. 1987-2011, bio, chem, engin, social)	227	
1/17/11	"green design principles"	(Yr. 1987-2011, bio, chem, engin, social)	85	
1/17/11	"ecological design" principles (all in	(Yr. 1987-2011, bio, chem, engin, social)	1860	

		Google Scholar		Science Direct
Date	**Search Term**	**Search Specs**	**# Of Results**	**# Of Results**
	quotes)			
1/17/11	principles, sustainable "integrated design" ("integrated design principles")	(Yr. 1987-2011, bio, chem, engin, social)	1350	
1/18/11	"cradle to cradle design" principles	(Yr. 1987-2011, bio, chem, engin, social)	110	
1/18/11	"principles of sustainable development"	(Yr. 1987-2011, bio, chem, engin, social)	4,110	
1/18/11	"sustainable engineering" principles	(Yr. 1987-2011, bio, chem, engin, social)	425	
1/18/11	"green engineering principles"	(Yr. 1987-2011, bio, chem, engin, social)	100	
1/19/11	"design for the environment" principles	(Yr. 1987-2011, bio, chem, engin, social)	706	
1/19/11	"biomimicry" principles	(Yr. 1987-2011, bio, chem, engin, social)	1810	

Articles and resources were selected from the initial searches that identified elements, principles, or frameworks for the search terms. In other words, the chosen literature was focused on development or identification of principles rather than specific applications. A three-step process defined in the literature review protocol was used to select studies from the database search:

1. Identify articles and publications through search strategies using established search terms.
2. Read the title, abstract, and key words to see if it is applicable to answering the guiding research questions.

3. If the article appears applicable, read full article, or skim publication for relevant chapters and use selection criteria to determine if the article should be included and extract principles.

A quality assessment checklist with well-defined criteria such as field of authors, years of experience, and number of citations, was used to assess the value of resources. As the resources continued to be reviewed additional criteria were added, and previously reviewed articles were assessed based on these new measures.

Resources meeting the assessment criteria were analyzed further to extract the principles or elements of whole systems design. The principles could be in the form of figures, lists, tables, charts, or summarized from the text. The original wording of the principles was maintained during the extraction process and included in the literature review excel database. The 49 sources selected during the literature review process and the corresponding source codes are displayed in Table **2**.

Table 2: Sources & Corresponding Source Code

Source #	**Source Code**	**Source Title**
1	E1	RMI's 10XE Principles
2	E2	Natural Edge WSD Suite
3	S1	Thinking in Systems - Chapter 7
4	A1	The Hanover Principles
5	E3	EPA's Principles of Green Engineering
6	SD1	The Bellagio Principles
7	S2	The Butterfly Effect' Creative Sustainable Design Solutions through Systems Thinking" - A Taxonomy for Systems Design
8	SD2	The Natural Step
9	A2	Wilderness Values from Gentle Architecture
10	A3	Ecological Design

Source #	Source Code	Source Title
11	E4	Design Through the 12 Principles of Green Engineering
12	A4	HOK Guidebook to Sustainable Design - Sustainable Design Goals
13	A5	The 10 Melbourne Principles
14	A6	Planning for Sustainability - Elements of the Sustainability Planning Approach
15	E5	Sustainable Development in Engineering: A Review of Principles and Definition of a Conceptual Framework for Sustainability in Engineering
16	E6	Design for Sustainability (DfS) - The Interface of Sustainable Production and Consumption - SCALES Core Principles
17	A7	Six Biophilic Design Element
18	E7	Biomimicry: Innovations Inspired by Nature
19	E8	Design Principles for Ecological Engineering
20	A8	The Philosophy of Sustainable Design
21	A9	From Ecocities to Living Machines: Principles of Ecological Design
22	A10	Principles and Practices of Ecological Design
23	SD3	Sustainable Cities: The Sanborn Principles for Sustainable Development
24	A11	Permaculture: Principles & Pathways Beyond Sustainability
25	E9	Ecological Engineering and Ecosystem Restoration
26	A12	City Building: Nine Planning Principles for the Twenty-first Century
27	E10	Applying the Principles of Green Engineering to Cradle to Cradle Design
28	M1	CERES Principles
29	A13	Ahwahnee Principles
30	E11	A Compilation of Design for Environment Principles and Guidelines
32	E12	12 Principles of Engineering for Sustainable Development Endorsed by Royal Academy of Engineers
33	SD4	Earth Charter Principles
34	SD5	The Daly Principles
35	E13	Sustainability Principles and Practice for Engineers
36	E14	Inherently Safer Design

Source #	Source Code	Source Title
37	E15	Materials selection and design for development of sustainable products - Guidelines for Sustainable Product Design
38	M2	Four ecosystem principles for an industrial ecosystem
39	E16	EcoDesign and The 10 Golden Rules
40	E17	Industrial Ecology – A Framework for Product and Process Design – Hardin Tibbs Framework
41	E18	Environmentally Sensitive Design - Leonardo Was Right! "Principles of Design for Disassembly "
42	M3	Eco-Efficiency and SME's in Nova Scotia, Canada - Elements of Eco-Efficiency
43	M4	Environmental Principles Applicable to Supply Chains Design and Operation
44	SD6	Achieving Sustainable Development
45	M5	A Roadmap to Natural Capitalism
46	S3	12 Living System Principles
47	S4	12 Habits of Mind
48	A14	Integrated Design MITHUN - Principles
49	E19	12 Principles of Green Chemistry

The principles extracted from resources were empirically coded and categorized into appropriate themes. Coding occurred in three iterations. A list of all the extracted principles was compiled and then skimmed for common key phrases and ideas to form an initial coding list. With the initial coding list, one coder went through the list of principles and assigned codes to principles that matched the initial coding list. Principles that did not fit under the initial coding list were analyzed further to discover common threads and ideas, which became additional codes. The initial coding list is shown in Table 3.

Table 3: Initial Coding List for Design Framework

Code # & Code Definition	Sources with Code
C1. Holistic Perspective - Consider the whole system, its components, and the relationship between them.	E1, E2, S1, A1, E3, SD1, S2, E4, A6, E6, A8, A11, A13, E12, E13, A14
C2. Shared Vision & Goals - Vision and goals for all pillars of sustainability should be defined clearly.	E1, E2, S2, SD1, A5, E8, E12, A14
C3. Direct & Open Communication - Communicate effectively with the design team and with all stakeholders.	S1, A1, SD1, S2, A5, E6, M1, SD4, E17, SD6, A14
C4. Broad Interdisciplinary Participation - Multiple disciplines, stakeholders, and perspectives should be included in the design process.	E1, S1, E3, SD1, S2, A3, A5, A6, E5, E6, E7, E12, SD4, E13, M1, E17, SD6, A14
C5. Share Information Openly & Clearly - Information is shared amongst designers and stakeholders.	S1, A1, SD1, S2, A5, E5, E6, E8, M1, SD4, A14
C6. Be a Teacher-Learner - practice mutual learning, understand sharing ideas as a means to creativity, and accept criticism.	S1, S2, A6, E6, SD4, A14
C7. Appropriate Scope - define the scope both temporally and spatially to address the problem and remain true to the vision and goals.	E1, S1, SD1, E4, A8, A12, E11, E12, E13, A14
C8. Place is Important - Understand, respect, and integrate when possible the local culture, geography, values, and history in the design.	S1, A1, A3, A4, A5, A6, E6, A7, E7, E8, A8, A9, SD3, A12, A13, SD4, M1, A14
C9. Get the Beat of the System - Understand system behavior, relationships, and systemic causes. Set baseline values and model the system.	E1, E2, S1, SD9, S2, A3, A6, E6, E13, M4, A14
C10. Focus on the End-Use - Focus on desired outcomes & purpose rather than on technology, products, and objects.	E1, E2, S2, E4, A4, E7, E13, M5, A14
C11. Design Non-Linearly - Design is an iterative and cyclic process.	E1, E2, S2
C12. Design on a ‘Clean Sheet’ - Be innovative, creative, and don’t imitate past designs.	E1, E3, A14
C13. Seek Simple, Elegant Solutions - Consider passive design and simpler systems.	E1, A1, E4, A4, E16, E18, M4, A14

C14. Learn from Nature - Mimic Nature's forms, processes, and systems. Consider how design fits with nature.	A1, S2, A3, A5, A7, A8, A9, A10, M5, A14
C15. Design for Flexibility & Adaptability - Systems must be flexible and be able to adapt to changing needs and circumstances.	E2, S2, A4, A9, SD3, A11, A12, SD6, A14
C16. Start Downstream, then Move Upstream - Start at the end-use to compound savings and benefits upstream.	E1, E2
C17. Rethink Waste - Eliminate waste; Waste = Food.	A1, E3, SD2, A2, E4, A4, E6, E7, A11, E10, A13, E11, SD5, E13, E15, M1, M4, M5, A14
C18. Multiple Benefits from Single Expenditures - Each part of the system should have multiple benefits and functions to be truly integrated.	E1, 32, E4, A4, A5, A11, M1 (MAYBE A1)
C19. Minimize Peak Demand - Minimize energy & resource demand during use.	E1, SD2, E4, E7, M1, E11, SD4, E13, E14, E15, M1, E16, M3, M4, A14
C20. Tunnel Through The Cost Barrier - greater resource efficiency can be justified by benefits other than initial capital costs.	E1, E12, A14
C21. Build in Feedback - Include feedback in the system to monitor and display system performance and behavior to allow for adaptability.	E1, S1, SD1, A2, A3, A5, E6, A9, SD3, A11, E17, SD6
C22. Non-hazardous - choose non-toxic materials; minimize hazardous materials.	A1, E3, SD2, E4, A4, E6, E7, A8, A10, M1, E11, E13, E14, E15, M2, E16, M3, A14
C23. Renewable - opt for renewable inputs (resources, materials, energy, etc.).	E3, A2, E4, A4, E5, E6, A8, A9, A10, A11, E10, M1, E11, SD5, E13, E14, E15, M2, E16, M3, M4
C24. Consider the entire life cycle - life cycle accounting.	A1, E3, S2, E6, A8, E13, E15, A14
C25. Accept responsibility for consequences of design decisions.	S1, A1, E6, E12
C26. Reward desired outcomes.	E1

C27. Diversity, complexity.	S1, E6, E7, A11, A12, E10, A13, M2, A14
C28. Maximize resource (energy, space, time, human capital, social capital) efficiency.	E4, E5, E6, E7, E8, A8, E11, SD5, E13, E15, M5
C29. Promote protection and restoration of systems where possible.	A2, A4, A5, E5, A9, A10, A12, M1, E11, SD4, E13

Examples of sources that were categorized under the code C14 – learn from nature are:

> Principle 8 of the Hanover Principles, "Understand limitations of design. No human creation lasts forever and design does not solve all problems. Those who create and plan should practice humility in the face of nature. Treat nature as a model and mentor, not an inconvenience to be evaded or controlled."

The above principle was coded under C14 because it refers to nature as a mentor, or something to be learned from and essentially mimicked, precisely what learn from nature means. Another principle categorized under the learn from nature code was:

> Principle 5 of the Melbourne Principles, "Model Cities on Ecosystems – build on the characteristics of ecosystems in the development and nurturing of healthy and sustainable cities."

This Melbourne principle again instructs designers to mimic nature's ecosystems in design of cities, i.e. learn from nature and build a model in its image. A sustainable business and management source that cited code C14, learn from nature was:

> From the *Roadmap to Natural Capitalism*, Step 2, "Shift to biologically inspired production models."

In the *Roadmap to Natural Capitalism* the authors are suggesting that companies mimic the production after biological ones, again learning from and mimicking nature. On the other hand, some principles were too specific to their design discipline to be considered relevant. Consider these two examples from the Ahwahnee Principles:

> Principle 3. "As many activities as possible should be located within easy walking distance to transit stops."
>
> Principle 4. "A community should contain a diversity of housing types to enable citizens from a wide range of economic levels and age groups to live within its boundaries."

They are very specific to community planning, and while valuable principles, they are not directly applicable to multiple types of design, and were subsequently not coded. However, it could be extracted that these principles allude to the code focus on end use. Ultimately, communities are for people, so ensuring that the community is designed to facilitate the use by people would be an application of that principle.

Once the codes were developed and the sources were analyzed, the preliminary framework was developed. Concept mapping was used to develop the logic and relationships amongst the codes and themes identified in the review process. Joseph D. Novak developed the concept mapping technique at Cornell University in the 1970s. Concept mapping is a way to visually represent the relationships between ideas, images, and words. According to Novak, a concept is "a perceived regularity (or pattern) in events or objects, or records of events or objects, designated by label" (Novak & Cañas, 2008). The label can be a word, symbol, or combination of words. He goes on to define propositions as "statements about some object or event in the universe, either naturally occurring or constructed" (Novak & Cañas, 2008). Propositions are made up of two or more concepts linked by words or phrases to form a significant statement. The concept maps begin in a hierarchical fashion, with the most broad topic or concept at the top, which is usually defined by a focus question (Novak & Cañas, 2008). From this focus question, concepts are branched off in more detail. Cross-links can be added to the map to demonstrate relationships between concepts across different segments or domains of the concept map (Novak & Cañas, 2008).

Scientists, mathematicians, or experts in any discipline use processes similar to concept mapping to construct new knowledge (Novak & Cañas, 2008). "Novak has argued that new knowledge creation is nothing more than a relatively high level of meaningful learning accomplished by individuals who have a well organized knowledge structure in the particular area of knowledge, and also a strong emotional commitment to persist in finding new meanings" (Novak & Cañas, 2008). This method was particularly useful because, while the knowledge from this research was not "new," the principles discovered in the literature had never before been organized coherently into a single coherent framework. Using this concept mapping technique, the codes, or themes were arranged to form a framework, or guiding principles of whole systems design by hand. The focus question guiding the process was "what is whole systems design?" From this question concepts were branched off in more detail, and relationships between concepts were demonstrated using cross-links.

The codes were also distributed to a group of engineering students (undergraduate and graduate students) enrolled in a sustainable energy class. The students had 20 minutes to develop individual concept maps, which were collected at the end of class. These concept maps were compared to the map developed by the independent researcher to reduce bias and consider alternative organizational frameworks. From this first concept map, codes were combined, eliminated, and grouped into broader categories, which evolved into a broad framework of whole systems design that outlined process, principles, and methods. For example, codes C3, C4, and C5 had the common theme of communication and information sharing amongst all users. These three codes were grouped to create one new code, or principle PRO3, which was titled "share all information with everyone." Two other codes displaying similar properties were grouped together. Code C19, "minimize peak demand for resources," and C28, "maximize resource efficiency," was combined into the final framework as code DM2.3, "Move resource impact towards zero."

After the codes underwent initial revisions, the principles were reexamined under the new codes. The principles from each source were coded and organized into the final framework describing the process, principles, and methods of whole systems design Much like in the first iteration of coding, some principles were still too specific to their individual applications to be included in the framework. The revised coding list used in analyzing the sources is shown in Table 4.

Table 4: Revised Coding List for Design Framework

Code # & Code Definition	**Sources with Code**
PRO1. Establish common goals—then align incentives.	E1, E2, SD1, A5, A9, A12, M1, E12, E17, A14
PRO2. Practice mutual learning.	SI, A5, E6, S4, A14
PRO3. Share all information with everyone.	E1, S1, E3, SD1, S2, A3, A5, A6, E5, E6, E7, A10, M1, E12, SD4, E13, E17, SD6, S4, A14

DP1. Focus on the fundamental desired outcome.	E1, SD1, S2, E4, A4, A6, E6, E7, E8, A10, A12, A13, E11, E12, E13, M3, SD6, M5, S3, A14
DP2. Learn from nature.	S2, A1, A2, S2, A3, A5, A7, E7, E8, A8, A9, A10, M5, S3, S4, A14
DP3. Apply systems thinking.	E1, E2, A1, E3, SD1, S2, S1, A6, E5 ,E6, E7, A8, A11, E9, A13, E12, E13, M2, E17, SD6, M5, S3, S4, A14
DM1.1. Define the scope to align with vision and desired outcomes.	E1, E2, S1, SD1, E6, E8, E9, A12, E12, E13, S4, A14
DM1.2. Design on a clean sheet.	E1, E3, S2, E12, A14
DM1.3. Start design analysis at the end-use and work upstream.	E1, E2, E3, E13,
DM2.1. Seek simple elegant solutions.	E1, E4, A4, A11, E14, E16, E18, M4, E19
DM2.2. Value place.	A1, E3, A3, A4, A5, A6, E6, A7, E7, E8, A8, A9, SD3, E9, A12, A13, SD4, M2, SD6, A14
DM2.3. Move resource impact towards zero.	E1, E3, SD2, E4, A4, A5, E5, E7, E8, A8, A10, E10, M1, A13, E11, SD4, SD5, E13, E14, E15, E16, E17, M3, M5, A14, E19
DM2.4. Rethink waste.	A1, E3, A2, E4, A4, E7, A11, E10, M1, A13, E11, E12, SD4, SD5, E13, E15, M2, E16, E17, M3, M4, M5, S3, E19
DM2.5. Use renewable inputs.	A1, A2, E4, A4, E5, E7, A9, A10, A11, E10, E11, E13, E15, M2, M3, E19
DM2.6. Use non-hazardous materials.	A1, E3, SD2, A2, E4, A4, SD3, M1, E11, SD4, E13, E14, E16, M3, A14, E19
DM3.1. Seek multiple benefits from single expenditures.	E1, S2, A2, E4, A4, E7, A9, A11, E9, A13, E13, M2, S3
DM3.2. Protect and restore natural, social, and economic systems.	A1, E3, SD2, A2, A4, A5, E5, E6, A9, A10, SD3, A12, M1, A13, SD4, E13, E15, E19
DM3.3. Build in feedback.	E1, E2, S1, SD1, S2, A2, A4, A5, E6, E7, SD3, A11, A12, M1, M4, SD6, S3, A14, E19

DM3.4. Consider the entire life-cycle of the system.	A1, E3, S2, A3, E4, E5, E6, A8, A10, SD3, E12, E15, E16, E17, M4, M5, S3, A14
DM3.5. Tunnel through the cost barrier.	E1, E12, A14

The codes were again arranged into a design framework by hand with concept mapping techniques. To reduce bias and again examine alternate perspectives about the relationship between the elements of the framework, the researcher and an advisor to the researcher conducted the final concept mapping. The advisor is a professor in civil engineering at Clemson University, with a background in construction and sustainability. He currently teaches several courses related to sustainable construction, energy, and systems within the civil engineering department and is comfortable with the topic of sustainable design. From the combined efforts of the researcher and advisor, a final whole system design framework was formed. The concept mapping technique was especially useful for creating a design framework because concept maps reveal connections and help people to visualize how individual concepts form a larger whole (Novak & Cañas, 2008).

2.2.3. Reporting the Review

The findings of this research will provide valuable knowledge for both members of academia and practicing design professionals. The implications, limitations, and conclusions for future applications of the design framework identified by this research were clarified and reported in this thesis report.

CHAPTER THREE: RESULTS AND ANALYSIS

"You may never know what results come of your action, but if you do nothing there will be no result"

- Mahatma Gandhi

Preliminary thematic analysis of resources obtained from the literature search has identified 3 overarching categories, with a total of 20 principles of whole systems design. A total of 501 principles have been extracted from 49 resources. The sources were selected based upon the review protocol, and assessed for their quality by the field of the authors, methods used, and publication type. The sources used to build the design framework and the corresponding quality assessment measures for each source are presented in Table **5**. Sources with strong content that focused on principles and design frameworks, authored by individuals with good experience in the field of sustainable design were selected for inclusion in the development of the whole systems design framework. Also, sources that employed broad participatory methods or other strong methodology to define sustainable design principles were selected to build the design framework.

Table 5: Sources Selected from Literature Search & Quality Assessment of Sources

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
1	E1	RMI's 10XE Principles	Report/ Web Page	Product, Process	No	Amory 35 years of experience in: Energy, Resources, Development, Environment; Hunter: Natural Capitalism, sustainable development, globalization, energy and resource policy.	RMI team having round table discussion of principles based on years of experience consulting with industry, designers, and government.	Engineering
2	E2	Natural Edge WSD Suite	Book & Website	Product, Process, System	No	The Natural Edge Project 2007- it is a collaborative partnership for research, education, and policy development on innovation for sustainable development.	This book provides a clear design methodology, based on leading efforts in the field, and is supported by worked examples that demonstrate how advances in energy, materials and water productivity can be achieved through applying an integrated approach to sustainable engineering.	Engineering
3	S1	Thinking in Systems - Chapter 7	Book	System	No	Donnella Meadows - Systems	Experience with systems, Literature review.	Systems Thinking
4	A1	The Hanover Principles	Report	System	No	William McDonough & Partners	The City of Hannover has commissioned "The Hannover Principles" to inform the international design competitions for World EXPO 2000 to ensure sustainable development..	Architecture, Planning, Urban Design
5	E3	EPA's Principles of Green Engineering	Web Page - From GE Conference	Product, Process	No	Engineers, scientists, government organizations (EPA)	Developed by more than 65 engineers and scientists at the Green Engineering: Defining the Principles Conference at Sandestin, Florida in May 2003.	Engineering
6	SD1	The Bellagio Principles	Web Page	Process, System	No	An international group of measurement practitioners and researchers from five continents came together at the Rockefeller Foundation's Study and Conference Center in Bellagio, Italy.	In November 1996, an international group of measurement practitioners and researchers came together to review progress to date and synthesize insights from practical ongoing efforts. The principles resulted and were unanimously endorsed.	Sustainable Development

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
7	S2	The Butterfly Effect' Creative Sustainable Design Solutions through Systems Thinking" - A Taxonomy for Systems Design	Conference Paper, 16th International Conference on Flexible Automation and Intelligent Manufacturing: FAIM 2006.	Product	Yes	M. McMahon - Manufacturing & Operations Engineering M. Hadfield - Department of Design, Engineering, & Computing	Literature review, interviews with designers. They tested the taxonomy by having professional designers complete a design exercise.	Engineering
8	SD2	The Natural Step	Webpage	System	No	The Natural Step is a non-profit organization whose vision is to create a sustainable human society. The essential mission is to promote understanding, competence, strategic planning and, above all, action towards sustainability.	International network of scientists unanimously and publically concluded that human society is damaging nature and altering life-supporting natural structures and functions in three fundamental ways. The system conditions can be reworded as basic sustainability principles guide anyone interested in moving towards sustainability.	Sustainable Development
9	A2	Wilderness Values from Gentle Architecture	Book	Product, Process	No	Malcolm Wells - father of modern earth-sheltered architecture	Experience & Literature Review	Architecture, Planning, & Urban Design
10	A3	Ecological Design	Book	Product, Process, System	No	Sim Van Der Ryn - Leader in Sustainable Architecture Stuart Cowan - Sustainable Systems Design for product, building, and landscape	Literature & expertise/experience	Architecture, Planning, & Urban Design
11	E4	Design Through the 12 Principles of Green Engineering	Article, Engineering Science & Technology (136)	Product, Process	Yes	Paul Anastas - professor in the chemistry department at the University of Nottingham in the UK and an assistant director at the White House Office of Science and Technology Policy; Julie Zimmerman - EPA STAR Fellow and research assistant in the Department of Civil and Environmental Engineering and the School of Natural Resources and Environment at the University of Michigan.	Consensus from the engineering field that started at a conference; Literature	Engineering

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
12	A4	HOK Guidebook to Sustainable Design - Sustainable Design Goals	Book	Product, Process	No	Sandra Mendler - Architect at HOK	Literature & expertise/experience in Sustainable Design	Architecture, Planning, & Urban Design
13	A5	The 10 Melbourne Principles	Report from UNEP Charrette	System	No	Experts in Urban Design, Planning, Development	Over 40 experts (in developed and developing countries) developed the principles in Melbourne, Australia on April 2, 2002 during the International Charrette sponsored by the United Nations Environment Programme & International Council for Local Environmental Initiatives. They were adapted at the local government session of the 2002 Earth Summit in Johannesburg as part of Local Action 21.	Architecture, Planning, & Urban Design
14	A6	Planning for Sustainability - Elements of the Sustainability Planning Approach	Book	System	No	Stephen M. Wheeler is Assistant Professor of Physical Planning and Design at the University of New Mexico.	Literature & expertise/experience	Architecture, Planning, & Urban Design
15	E5	Sustainable Development in Engineering: A Review of Principles and Definition of a Conceptual Framework for Sustainability in Engineering	Article, Environmental Engineering Science	System	Yes	Bruno Gagnon - Civil Engineering; Roland Leduc - Civil Engineering; Luc Savard - Economics	Literature Review	Engineering
16	E6	Design for Sustainability (DfS) - The Interface of Sustainable Production and Consumption - SCALES Core Principles	Article, Journal of Cleaner Production 18 (2010)	Product, Process	Yes	Joachim H. Spangenberg - Macroeconomist educated in Biology/Ecology (SERI); Alastair Fuad-Luke - Sustainable design consultant, facilitator, educator, writer, activist (ICIS); Karen Blincoe - Educator, designer, & environmentalist	Literature Review & Survey	Engineering

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
17	A7	Six Biophilic Design Element	Book	Product, Process	No	Stephen R Kellert - social ecology - School of Forestry & Environmental Studies at Yale. CEO of Biological Capital.	Literature & expertise/experience	Architecture, Planning, & Urban Design
18	E7	Biomimicry: Innovations Inspired by Nature	Book	Product, Process, System	No	Janine Benyus - natural sciences writer, innovation consultant.	Literature & expertise/experience	Engineering
19	E8	Design Principles for Ecological Engineering	Article, Ecological Engineering	Product, Process	Yes	Scott D. Bergen & James L. Fridley - Forest Management & Engineering Division; Susan M. Bolton - Center for Sustainable Studies University of Washington	Their ideas & influences from other authors in the field.	Engineering
20	A8	The Philosophy of Sustainable Design	Book	Product, Process, System	No	Jason McLennan - CEO of the Cascadia Green Building Council, a leading organization in the field of green building and sustainable development. An international thought leader in the green architecture movement. Work in sustainable design field has been published or reviewed in dozens of journals, magazines conference proceedings and books. He is a former Principal at BNIM Architects, one of the founders of the green design movement in the United States, worked on many of the leading high performance projects in the country including LEED Platinum, Gold and zero energy projects.	Literature from field of sustainable design & years of consulting for sustainable design firm.	Architecture, Planning, & Urban Design
21	A9	From Ecocities to Living Machines: Principles of Ecological Design	Book	System	No	Nancy Jack Todd - environmental activist; John Todd - biologist; known world-wide for their leadership in the restoration of pure water, urban design, bioremediation of aquatic environments, food production	Experience/Expertise	Architecture, Planning, & Urban Design

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
22	A10	Principles and Practices of Ecological Design	Article, Environmental Review	System, Product, Process,	Yes	F. Shu-Yang and B. Freedman from Department of Biology & School of Environment, Dalhousie University Canada	Literature Review & discusses applications and examples	Architecture, Planning, & Urban Design
23	SD3	Sustainable Cities: The Sanborn Principles for Sustainable Development	Website	System	No	Amory Lovins – Founder RMI, resource for sustainable planning and design, renewable energy policy; Perry Bigelow - President of Bigelow Homes, builder and developer of sustainable homes; John Knott, developer of Dewees Island, a fully-sustainable island off the coast of SC, and co-developer of the first fully-sustainable city restoration in North Charleston; Bill Browning - Founder/ Director of Green Building Team for RMI, author of two books on sustainable development; Richard Register - Founder and President of Ecocity Builders, author of Ecocities – Building Cities in Balance with Natures; Liz Gardener - Manager of Water Conservation Programs for the Denver Water Board; Paul MacCready - Founder and President of Aerovironment, developer of futuristic transportation systems; Ned Nisson - Founder of Energy Design Update, a publication on new systems for sustainable architecture and planning.	In 1994, the National Renewable Energy Laboratory (NREL) gathered together a group of nationally known experts in every field related to sustainability. The group, selected at NREL's request by Barbara Harwood, included such luminaries as Amory Lovins, Perry Bigelow, John Knott, Bill Browning, Richard Register, Liz Gardener, Paul MacCready, Ned Nisson, Mark Ledbetter,* and others, developed a pathway, including specific principles, for those wishing to pursue sustainable development. Those principles, below, have been used around the world by cities, towns, and groups, to move toward a more sustainable future.	Sustainable Development
24	A11	Permaculture: Principles & Pathways Beyond Sustainability	Book	Product, Process, System	No	David Holmgren - ecologist, ecological design engineer and writer. Co-originator of the permaculture concept with Bill Mollison. Through the spread of permaculture around the world, his environmental principles have exerted a global influence.	Literature Review & expertise/experience	Architecture, Planning, & Urban Design

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
25	E9	Ecological Engineering and Ecosystem Restoration	Book	System	No	Mitsch, W.J. ; Jorgensen, S.E.	Literature Review & expertise/experience	Engineering
26	A12	City Building: Nine Planning Principles for the Twenty-first Century	Book	System	No	John Kriken - Architecture/Environmental Design/Urban Design	Literature Review & expertise/experience	Architecture, Planning, & Urban Design
27	E10	Applying the Principles of Green Engineering to Cradle to Cradle Design	Article, Environmental Science & Technology	Product, Process	Yes	William McDonough & Michael Braungart - Design Chemistry Founders; Paul T, Anastas - Assistant Director for Environment at the White House; Julie B. Zimmerman - Engineer with the EPA	Literature Review & expertise/experience	Engineering
28	M1	CERES Principles	Website/Report	Product, Process, System	No	Ceres (pronounced "series") is a national network of investors, environmental organizations and other public interest groups working with companies and investors to address sustainability challenges such as global climate change, whose mission is to: Integrate sustainability into capital markets for the health of the planet and its people.	First published in the fall of 1989, the Ceres Principles are a 10-point code of corporate environmental ideals to be publicly endorsed by companies as an environmental mission statement or ethic. Over 50 companies have endorsed the Ceres Principles including 13 Fortune 500 firms that have adopted their own equivalent environmental principles.	Enviro. Management & Business
29	A13	Ahwahnee Principles	Website/Report	System	No	Peter Calthorpe, Michael Corbett, Andres Duany, Elizabeth Moule, Elizabeth Plater-Zyberk, and Stefanos Polyzoides - Architecture, New Urbanism	Written in 1991 by the Local Government Commission, paved the way for the Smart Growth and New Urbanism. A blueprint for elected officials to create compact, mixed-use, walkable, transit-oriented developments in local communities. Experience & expertise.	Architecture, Planning, & Urban Design

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
30	E11	A Compilation of Design for Environment Principles and Guidelines	Conference Paper, ASME 2008 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference	Product, Process	Yes	Cassandra Telenko, Carolyn C. Seepersad; Michael E. Webber - Mechanical Engineering at UT Austin	Mind-mapping and Literature Review	Engineering
32	E12	12 Principles of Engineering for Sustainable Development Endorsed by Royal Academy of Engineers	Book	System	No	The Royal Academy of Engineering	Literature review of SD principles and experience/examples of principles in practice.	Engineering

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
33	SD4	Earth Charter Principles	Report	System	No	Wide Participatory Process - All fields	Product of a 10-year, worldwide, cross cultural dialogue on common goals and shared values. It began as a UN initiative, but it was carried forward and completed by a global civil society initiative. It was finalized and launched as a people's charter in 2000. The most inclusive and participatory process ever associated with the creation of an international declaration and is the primary source of its legitimacy as a guiding ethical framework. It is endorsed by over 4,500 organizations, including many governments and international organizations. An increasing number of international lawyers recognize that the Earth Charter is acquiring the status of a soft law document.	Sustainable Development
34	SD5	The Daly Principles	Section in Book, Ecological Economics	System	No	Herman Daly - Ecological economics; professor at UMD school of public policy	Experience & Literature review	Sustainable Development

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
35	E13	Sustainability Principles and Practice for Engineers	Article, IEEE Technology and Society Magazine	Product, Process, System	Yes	Carol Boyle - Deputy Director at the International Centre for Sustainability Engineering and Research, Department of Civil and Environmental Engineering, University of Auckland, Auckland, New Zealand; Gerry Te Kapa Coates - Director at Wise Analysis Limited, and was President of the Institution of Professional Engineers New Zealand.	The Institute of Professional Engineers of New Zealand (IPENZ) Presidential Task Force on Sustainability and Engineering met in 2003 to raise consciousness of engineers in terms of applying sustainability principles in their daily work and thinking. The task force (5 members) developed the principles based on a literature review of accepted sustainability principles relevant to professional engineers' roles. Also discussed how the principles should be put into practice.	Engineering
36	E14	Inherently Safer Design	Article, Chemical Engineering Journal	Product, Process	Yes	J. García-Serna, L. Pérez-Barrigón, M.J. Cocero - The green engineering group Departamento de Ingeniería Química y Tecnología del Medio Ambiente, Facultad de Ciencias, Universidad de Valladolid, Valladolid, Spain	Literature Review	Engineering
37	E15	Materials selection and design for development of sustainable products - Guidelines for Sustainable Product Design	Article, Materials & Design	Product, Process	Yes	Lennart Y. Ljungberg - Department of Technology and Society (Integrated Product Development), University of Skode, Sweden	Literature Review	Engineering
38	M2	Four ecosystem principles for an industrial ecosystem	Article, Journal of Cleaner Production (121)	System	Yes	Jouni Korhonen - University of Joensuu, Department of Economics	Reflection of ecosystem principles in IE.	Enviro. Management & Business

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
39	E16	EcoDesign and The 10 Golden Rules	Article, Journal of Cleaner Production	Product, Process	Yes	Conrad Luttropp - KTH/Machine Design, Sweden; Jessica Lagerstedt - Bombardier Transportation Department Sweden	A pedagogic summary of many of the guidelines that can be found in company guidelines and handbooks referred to in the preceding literature list. They are generic and must be customized to be directly useful in product development. Literature Review on EcoDesign guidelines and derived from insights gained from Luttropp's design experiences during 27 years in the design and teaching areas and especially EcoDesign experience during the last 12 years.	Engineering
40	E17	Industrial Ecology – A Framework for Product and Process Design – Hardin Tibbs Framework	Article, Journal of Cleaner Production (100)	Product, Process	Yes	John R. Ehrenfeld - MIT Program on Technology, Business, and Environment	Literature Review	Engineering
41	E18	Environmentally Sensitive Design - Leonardo Was Right! "Principles of Design for Disassembly "	Article, Materials & Design (12)	Product, Process	Yes	Brian S. Thompson - Department of Mechanical Engineering, Michigan State	Literature Review	Engineering
42	M3	Eco-Efficiency and SME's in Nova Scotia, Canada - Elements of Eco-Efficiency	Article, Journal of Cleaner Production (34)	Product, Process	Yes	Raymond Cote ́ & Aaron Booth- Eco-Efficiency Centre, School for Resource and Environmental Studies, Dalhousie University; Bertha Louis - Department of Biological Engineering, Dalhousie University	Literature review, originally these were identified by World Business Council on Sustainable Development.	Enviro. Management & Business
43	M4	Environmental Principles Applicable to Supply Chains Design and Operation	Article, Journal of Cleaner Production (43)	Product, Process	Yes	Giannis T. Tsoulfas, Costas P. Pappis - University of Piraeus, Department of Industrial Management,	Literature Review	Enviro. Management & Business

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
44	SD6	Achieving Sustainable Development	Article, Landscape Planning (1)	System	Yes	Peter Jacobs - Architecture	An international workshop organized by the Commission on Environmental Planning, IUCN, convened in April 1984 to address the question "How do we achieve sustainable development?" 45 participants, 17 countries representing international organizations, government agencies, universities and private companies involved in development and living resource conservation examined the relationship between the goals of sustainable development and the theory and practice of environmental planning.	Sustainable Development
45	M5	A Roadmap to Natural Capitalism	Article, Harvard Business Review (228)	System	Yes	Amory: Energy, Resources, Development, Environment; Hunter: Natural Capitalism, sustainable development, globalization, energy and resource policy, economic development, climate change; Paul Hawken: environmentalist, journalist, entrepreneur, economic development, industrial ecology, and environmental policy	Experiences & Case Studies of businesses taking this approach successfully.	Enviro. Management & Business
46	S3	12 Living System Principles	Website	System	No	Linda Booth Sweeney - Educator, Writer, Expert in Systems Thinking/ Systems Design	Literature & Experience with Systems Thinking & Education	Systems Thinking
47	S4	12 Habits of Mind	Website	System	No	Linda Booth Sweeney - Educator, Writer, Expert in Systems Thinking/ Systems Design	Literature & Experience with Systems Thinking & Education	Systems Thinking

Source #	Source Code	Source Title	Type of Source	Scale of Sustainability	Peer Reviewed	Authors - Field of Authors	Method	Field of Design
48	A14	Integrated Design MITHUN - Principles	Book	Product, Process, System	No	MITHUN an innovative US architecture design firm (sustainable design) David R. Macaulay is the staff writer for ecotone publishing, a writer/marketer for more than 25 years. Specializes in writing about green buildings and sustainable design.	Experience in design & exemplary firm principles	Architecture, Planning, & Urban Design
49	E19	12 Principles of Green Chemistry	Book	Product, Process	Yes		Literature Review, discussion by experts.	Architecture, Planning, & Urban Design

The whole systems design framework that emerged from the literature review is organized into three overarching categories of design process, design principles, and design methods. It is comprised of 20 total principles or elements and represents the literature in the fields of sustainable development, systems thinking, engineering, architecture, urban design, planning, and sustainable management.

3.1. Design Process

The following principles identified throughout the literature describe the process of whole systems design. These principles do not outline the actual whole systems design process, but rather emphasize essential elements of the process itself. Overall, the whole systems design process is founded on the sharing of goals, learning, and information.

3.1.1. Establish common goals—then align incentives.

This principle means that stakeholders and members of the design team should define shared visions and goals based upon all three pillars of sustainability: economic, ecologic, and social (International Institute for Sustainability [IISD], 1996; Lovins et al., 2010; United Nations Environment Programme [UNEP] & International Council for Local Environmental Initiatives [ICLEI], 2002). Once visions and goals are outlined, incentives should be put into place to ensure that the desired outcomes are achieved during the design process (Kriken, 2010; Lovins et al., 2010;).

3.1.2. Practice mutual learning.

Establishing the right mindset to undertake whole systems design is crucial. Members of the design team must be "teacher-learners" by practicing mutual learning, understanding the sharing of ideas as a means to creativity, and accepting input and criticism from team members (Meadows, 2008, UNEP & ICLEI, 2002). This means bringing passion, and leaving behind the ego; the designer should act as an integrator, mentor, student, and partner that works to build relationships and is eager to learn (Macaulay, 2008).

3.1.3. Share all information with everyone.

Openness of communication, information, and participation is another essential component of whole systems design. Communication and information sharing should be direct, open, and effective (Meadows, 2008). This principle means shattering silos, collaborating to ask, solve and interact with more ideas (Macaulay, 2008). Participation should be broad and interdisciplinary, valuing diverse perspectives and including multiple stakeholders throughout all stages of the design process (Anastas & Zimmerman, 2003; IISD, 1996; Lovins et al 2010; McMahon & Hadfield, 2007). Honoring every voice in the design process ensures that the design team recognizes diverse and changing values and encourages decision makers to follow the design with appropriate actions (IISD, 1996; Ryn & Cowan, 2007).

3.2. Design Principles

Principles are defined as fundamental, primary, or general laws or truths from which others are derived. The three design principles below are the foundation from which the design method principles were derived.

3.2.1. Focus on the fundamental desired outcome.

This principle, called focus on the end-use, by the Rocky Mountain Institute, requires designers to focus their attention and efforts on achieving the desired outcomes and purpose of the project rather than on technology, products, and objects. Focusing on the fundamental desired outcome means creating beauty and spirit by prioritizing design elements that are purposeful, relevant, and contribute to a greater whole (Macaulay, 2008). By acknowledging the values and purposes that motivate design, designers can create something meaningful and compatible with the larger system (Bergen et al, 2001; Kriken, 2010, Macaulay, 2008;).

3.2.2. Learn from Nature.

This principle, also known as biomimicry, encourages designers to mimic the forms, processes, and systems found in Nature and to consider how their design fits with Nature (McLennan, 2004; McMahon & Hadfield, 2007). Nature minimizes toxicity, celebrates diversity, curbs demand, and makes connections (Benyus, 1998; Macaulay, 2008). Even the interdisciplinary nature of the design team reflects Nature's properties: it is interdependent, comprehensive, and thinks like an ecosystem (Macaulay, 2008). Nature is not to be treated as an inconvenience to be avoided or manipulated, but rather as a model and a mentor that can lead to healthy and sustainable solutions (McDonough, 1992; Todd, 1994; UNEP & ICLEI, 2002).

3.2.3. Apply systems thinking.

Systems thinking means that designers consider the whole system, it's components, and the relationship between them throughout the design process (Calthorpe et. al, 1991; Environmental Protection Agency [EPA] 2011; Lovins et al., 2010; TNEP Engineering Sustainable Solutions Program, 2011). In the words of Donella Meadows, designers should "get the beat of the system," meaning they should understand system behavior and use baseline values to model the system they are designing (Meadows, 2008). This principle also means adopting a holistic approach to design by moving from patterns to details, examining problems from multiple perspectives, and replacing linear thinking with cyclical design (Ehrenfeld, 1997; Holmgren, 2002; Lovins et al., 2010; McMahon & Hadfield, 2007; Spangenberg et al, 2010). Expanding the design consideration to consider distant effects is essential to understanding how designs will interact with and impact the natural systems around them (McDonough, 1992).

3.3. Design Methods

A method is defined as a procedure, technique, or way of doing something, especially in accordance with a definite plan. The following principles relate to the methods used by whole-system designers.

3.3.1. Define the scope to align with vision and desired outcomes.

Defining an appropriate scope is essential to the success of any planning and design process. This often involves pushing conventional design boundaries, and questioning everything to remain true to the purpose of the project (Macaulay, 2008). Designers should define the scope both temporally and spatially to address the problem and remain true to established visions and goals (Anastas & Zimmerman, 2003; Lovins et al., 2010; Mitsch, 2004). This means having both short and long-term time horizons; a long enough time horizon should be adopted to respond to the needs of both current and future generations (IISD, 1996; Kriken, 2010; Meadows, 2008). Aside from spatial and temporal boundaries, designers must also consider ecologic, social, and economic factors that align with the goals and visions of the project when defining the scope.

3.3.2. Design on a clean sheet.

A phrase coined by the Rocky Mountain Institute, designing on a clean sheet means to be innovative, creative, and not imitate past designs (Lovins et al., 2010;). Beginning with a clean sheet removes preconceptions and limitations to creativity and innovation in design. As practiced at the Mithun architecture firm, it means growing an idea, only asking questions, removing preconceptions and assumptions, testing and exploring every possibility, and allowing ideas to evolve and shape over time (Macaulay, 2008).

3.3.3. Start design analysis at the end-use and work upstream.

From years of consulting and design experience, RMI has found that as energy and resources move from supply (upstream) to end-use (downstream), losses of these resources are compounded through each successive step. They suggest that designers turn these compounding losses into compounding benefits by starting savings and benefits first downstream and then move upstream (Boyle & Coates, 2005; EPA, 2011; Lovins et al., 2010; "TNEP Engineering Sustainable Solutions Program," 2011).

3.3.4. Seek simple elegant solutions.

Radical simplicity means utilizing passive design and simpler systems to achieve the desired outcomes and purpose of the design (Anastas, 2000; Lovins et al., 2010; Mendler, et al, 2006; Thompson, 1999; Tsoulfas & Pappis, 2006). This usually results in cost, time, and resource savings and reduces waste.

3.3.5. Value place.

A principle more commonly practiced by urban designers, planners, and architects, valuing place means to understand, respect, and integrate when possible the local culture, geography, values, and history into the design (EPA, 2011; McDonough, 1992). More often than not, the best solutions begin with paying attention to unique qualities of place and building off of them (Ryn & Cowan, 2007; UNEP & ICLEI, 2002; Wheeler, 2004). Creating and preserving a sense of identity for a place that is both unique and memorable is central to meeting a most basic human yearning for home and connectedness (Kellert, 2008; Kriken, 2010). This principle places value in people and includes the human element in design to strengthen community and reinforce connectedness (Macaulay, 2008).

3.3.6. Move resource impact towards zero.

Designing for sustainability requires shifting our resource impacts towards zero. Designers can achieve this by minimizing the demand for resources while maximizing the efficiency of resources used (Anastas, 2000; Gagnon et al, 2009; Lovins et al., 2010; Luttropp & Lagerstedt, 2006; Lovins et al, 1999; The Earth Charter, 2000). The principle implies increasing the efficiency of a design though out its life cycle including the usage phase. Also, renewable resources should be consumed at rates below the regeneration rate (Ceres Principles, 1989; Cote & Louis, 2006; Daly, 1991; Shu-Yang et al, 2004).

3.3.7. Rethink waste.

This principle requires a radical re-evaluation of waste. As suggested by William McDonough, waste is food. The waste of one process or component can become the food or input for another part of the system so that the entire system can shift towards zero waste (Benyus, 1998; Holmgren, 2002; Lovins et al, 1999; Wells, 1981). Designers should promote the three R's: reduce, re-use, and recycle, but should also design for up-cycling, which is the conversion of waste and old materials into new materials or products of better quality or a higher environmental value (McDonough et al, 2003).

3.3.8. Use renewable inputs.

Designers should choose inputs for their designs that are from renewable sources when possible. These renewables shouldn't be used beyond their regeneration rate to ensure their availability for future generations (Daly, 1991; Gagnon et al, 2009; Holmgren, 2002; Korhonen, 2001; Ljungberg, 2007; Mendler et al, 2006; Telenko et al, 2008).

3.3.9. Use non-hazardous materials.

Whenever possible, inputs for design should be non-hazardous to human, environmental, and economic health (García-Serna et al, 2007; The Four System Conditions, 1991). The precautionary principle should be used to reduce risk as much as possible and where toxic substances are unavoidable, closed loops should be used (Boyle & Coates, 2005; Luttropp & Lagerstedt, 2006).

3.3.10. Seek multiple benefits from single expenditures.

For truly integrated, whole systems design, components should perform more than function and have multiple benefits for the system (Anastas & Zimmerman, 2003; Lovins et al., 2010; Sweeney, 2011). Integrating the elements of a design leads to synergistic solutions that can often reduce costs, and negative impacts associated with a project.

3.3.11. Protect and restore natural, social, and economic systems.

Designs should not harm the natural, social, or economic systems that they are a part of, but rather they should work to heal them (Apul, 2010; EPA, 2011; Ljungberg, 2007; McDonough, 1992; National Renewable Energy Laboratory [NREL], 1994; Shu-Yang et al, 2004; Todd, 1994).

3.3.12. Build in feedback.

Feedback is a central concept to systems thinking. Designers should include feedback to allow for flexibility, adaptability, resiliency, and diversity of their designs. Designing to include feedback creates future options, promotes collective learning, and informs decision makers (IISD, 1996; Lovins et al., 2010; Meadows, 2008; TNEP Engineering Sustainable Solutions Program, 2011).

3.3.13. Consider the entire life-cycle of the system.

Designers should design for the entire life-cycle of their solutions and use life-cycle accounting (Anastas & Zimmerman, 2003; Dodds & Venables, 2005; Ehrenfeld, 1997; EPA, 2011; McDonough, 1992; McMahon & Hadfield, 2007; Ryn & Cowan, 2007). This holistic method encourages designers to trace the direct and indirect social, economic, and environmental impacts associated with their design (Ryn & Cowan, 2007).

3.3.14. Tunnel through the cost barrier.

A strategy of 'Natural Capitalism,' tunneling through the cost barrier means that designers can justify greater resource efficiency by achieving benefits other than initial capital costs. Integrative, whole systems design allows for very large resource savings at a lower cost than small resource savings typical of conventional siloed design (Lovins et al., 2010; Lovins et al, 1999; Macaulay, 2008).

3.4. The Design Framework

These principles discovered in the literature are broad enough to be applicable across a variety of design disciplines, including the design of sustainable cities and infrastructure by engineers, architects, planners and policy makers. The principles are visually organized into a framework outlining the process, principles, and methods of whole systems design shown in Figure **3**. Related processes, principles, and methods are arranged under the same columns and are also indicated by color.

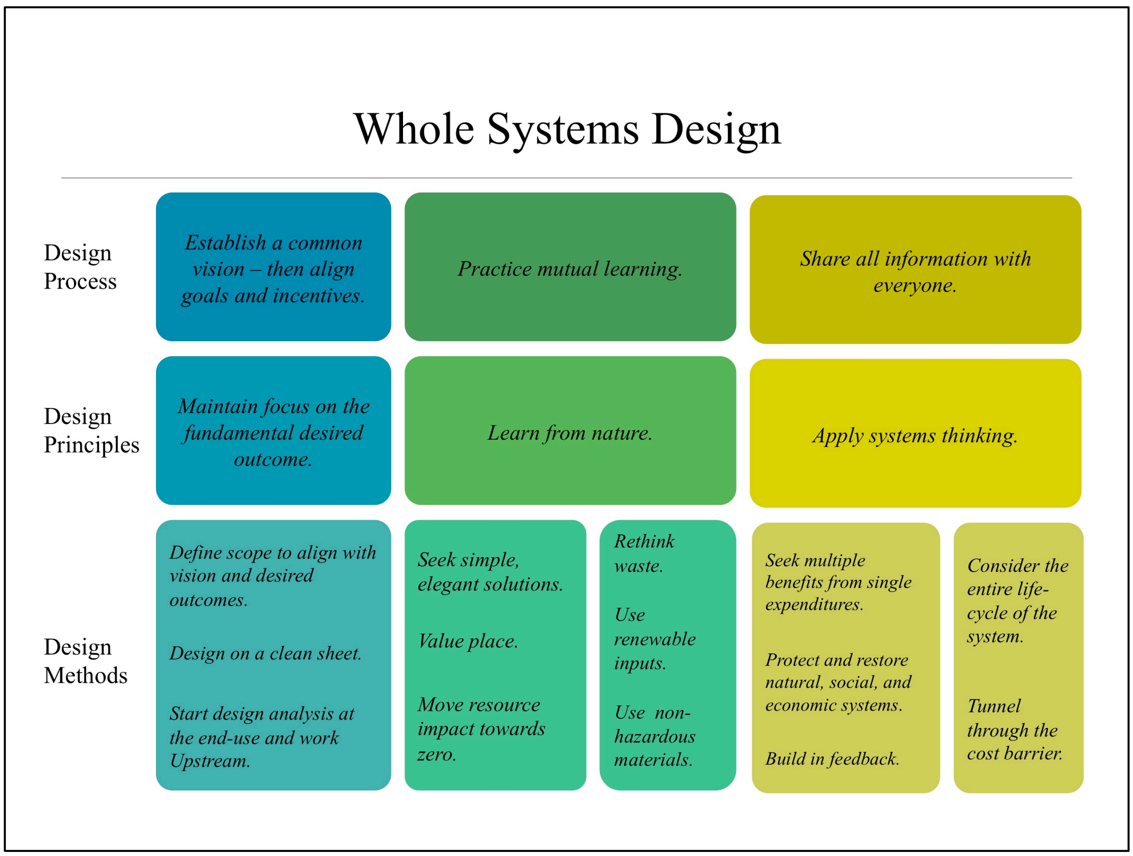

Figure 3: Whole systems Design Framework

For example, consider the first column in Figure **3**, the process in that column is establish a common vision – then align goals and incentives. This is the first step in any good planning or design process, so it's naturally suited to be the first element of the framework. The first principle beneath this first process is: maintain focus on the fundamental desired outcome. This principle was placed in the first column because it relates back to the initial vision and goals that the design team defines in the first step of the design process. Three design methods were grouped under this first column: (1) define scope to align with vision and desired outcomes, (2) design on a clean sheet, and (3) start design analysis at end-use and work upstream. These methods were grouped in the first column because they all refer to the start of design analysis, i.e. how designers should begin.

Similar logic was used to group the processes, principles, and methods in columns two in three. In column two, the common threads were related to a learner's mindset, and in particular learning from nature. The third column processes, principles, and methods are linked together by a holistic, systems approach. As indicated by the row labels, elements of the framework are also related across rows. The rows were grouped based upon whether the element of the framework referred to the design process, was a design principle to be considered, or was a method that should be utilized by designers throughout the process.

Understanding how each category of sources contributed to the design framework is both interesting and essential to understanding how the framework was created. This analysis highlights commonalities to show where designers are in agreement, building consensus for the framework. But it also illuminates the differences in design approaches and perspectives amongst the different disciplines to fill in the gaps and build a framework that can help designers meet the challenges of sustainable design. The breakdown of how each category of sources (engineering, architecture, planning, urban design, sustainable development, systems thinking, and sustainable management) mapped onto the framework is indicated in Figure **4** through Figure **9**. At least one of the engineering sources identified each of the components of the framework as demonstrated by the shading in Figure **4**.

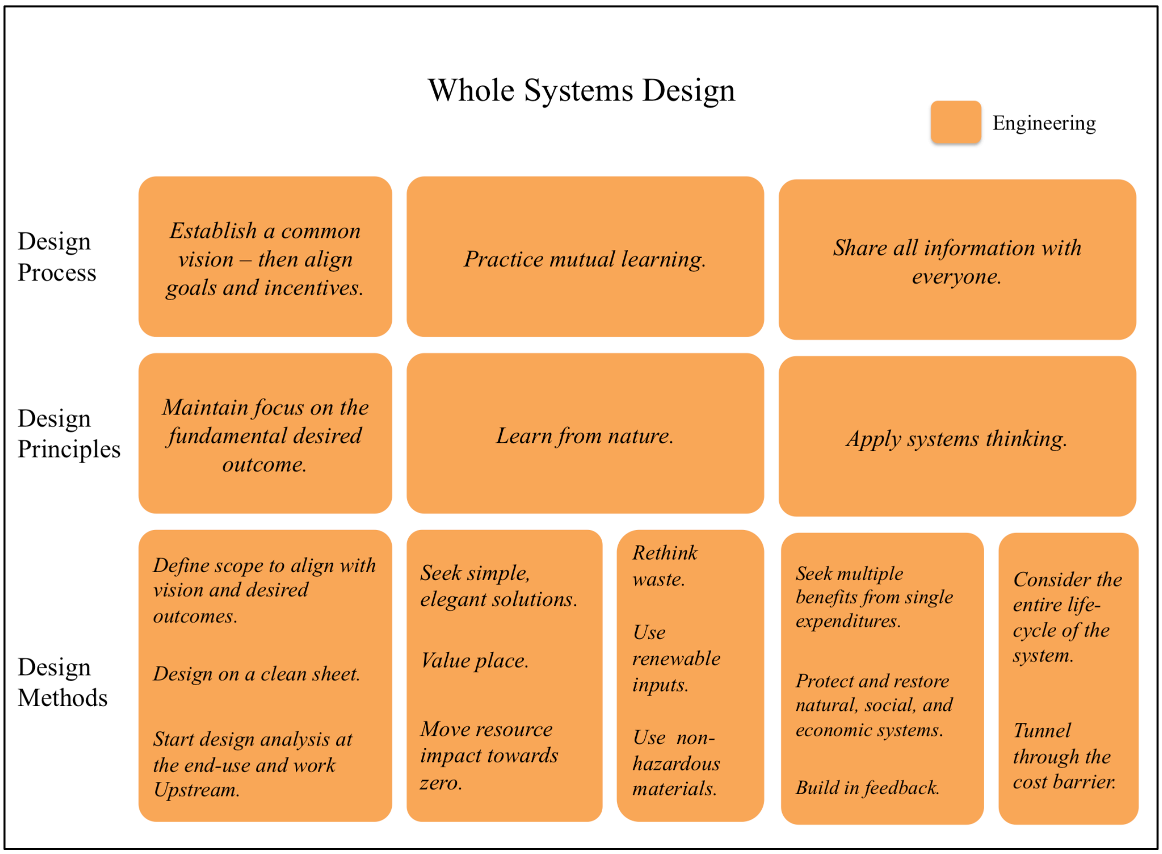

Figure 4: Components of the Framework Found in Engineering Sources

The engineering and architecture, planning, and urban design sources represented the largest categories of sources. There were nineteen sources categorized under engineering design, and fourteen sources representing the field of architecture, planning, and urban design. Interestingly, all but one of the framework components, start design analysis at the end-use and work upstream, were identified in the architecture, planning, and urban design sources as shown in Figure **5**. This element may have been absent in the selected sources because these design disciplines often don't focus their efforts on detailed technical analysis of the systems they are designing. The principles that guide their design are often broader and focus on social and environmental issues surrounding their designs.

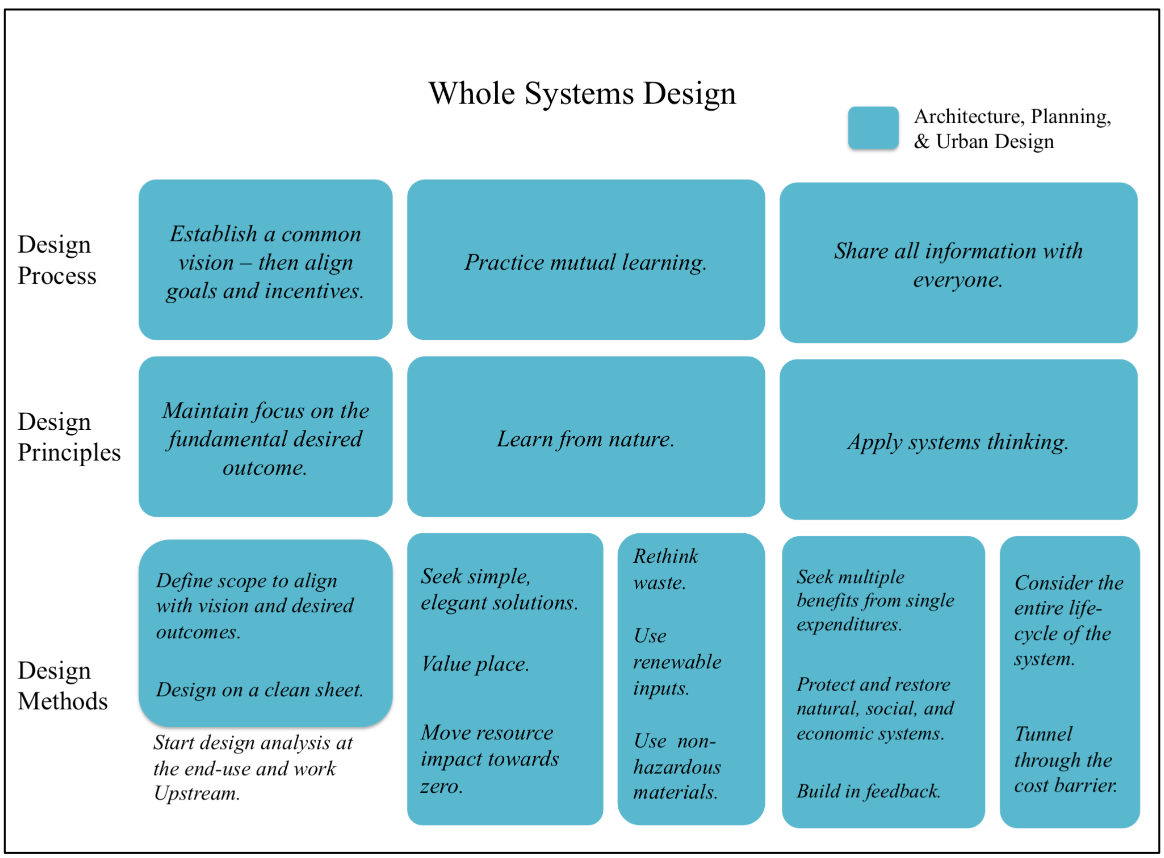

Figure 5: Components of Framework Found in Architecture, Planning, & Urban Design Sources

The sustainable development sources, of which there were a total of six, identified twelve of the components of the framework as demonstrated by Figure **6**. Even though there were only six sources for this category, the largest and most widely accepted sustainable development principles were used to develop the design framework. A likely reason that only twelve components of the framework were identified may have been that sustainable development doesn't necessarily focus on the design of products, or physical objects, but is more often related to policy and intangible design.

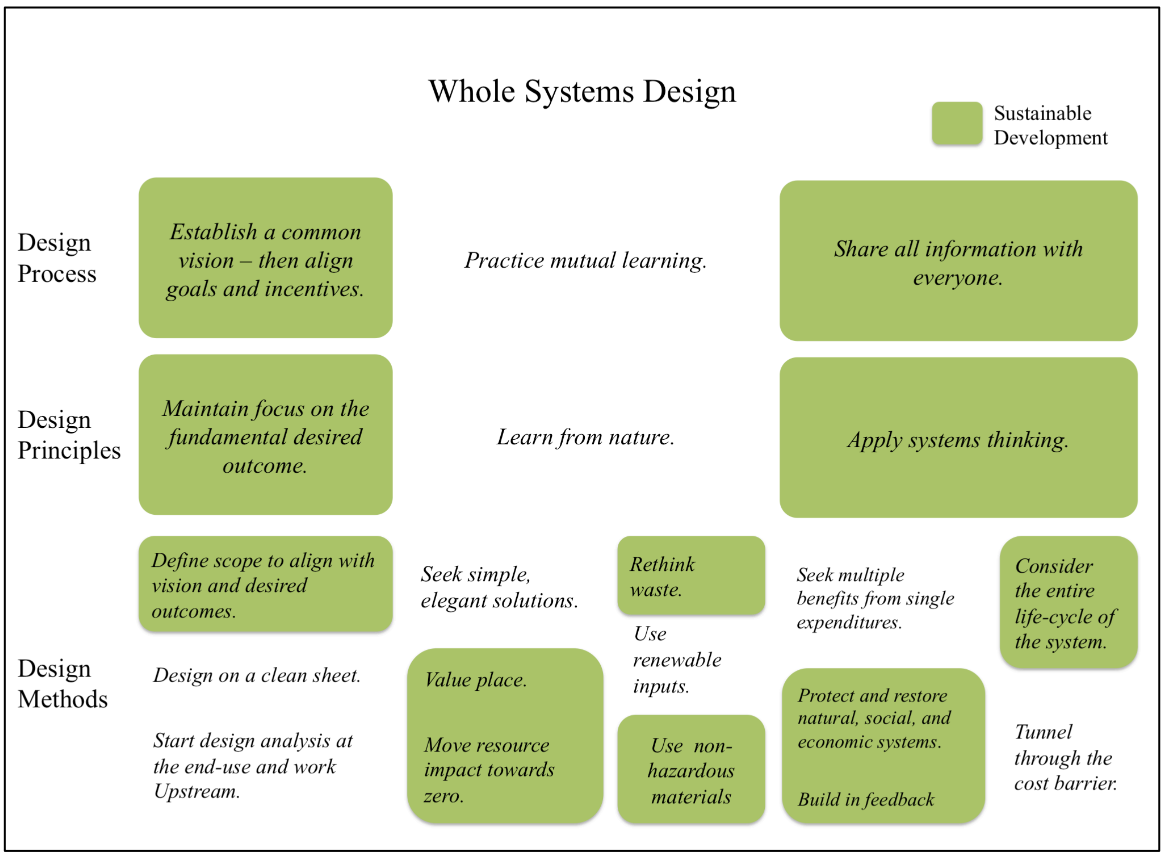

Figure 6: Components of Framework Found in Sustainable Development Sources

The components of the framework identified by the four systems thinking sources are shown in Figure **7**. The systems thinking sources primarily identified elements related to process and principle as opposed to design methods. This trend was anticipated because systems' thinking is a process or approach that considers the interrelatedness of individual parts within the context of a greater whole. Generally principles of systems thinking do not prescribe methods to design for economic, social, or environmental sustainability, but rather suggest ways to think holistically.

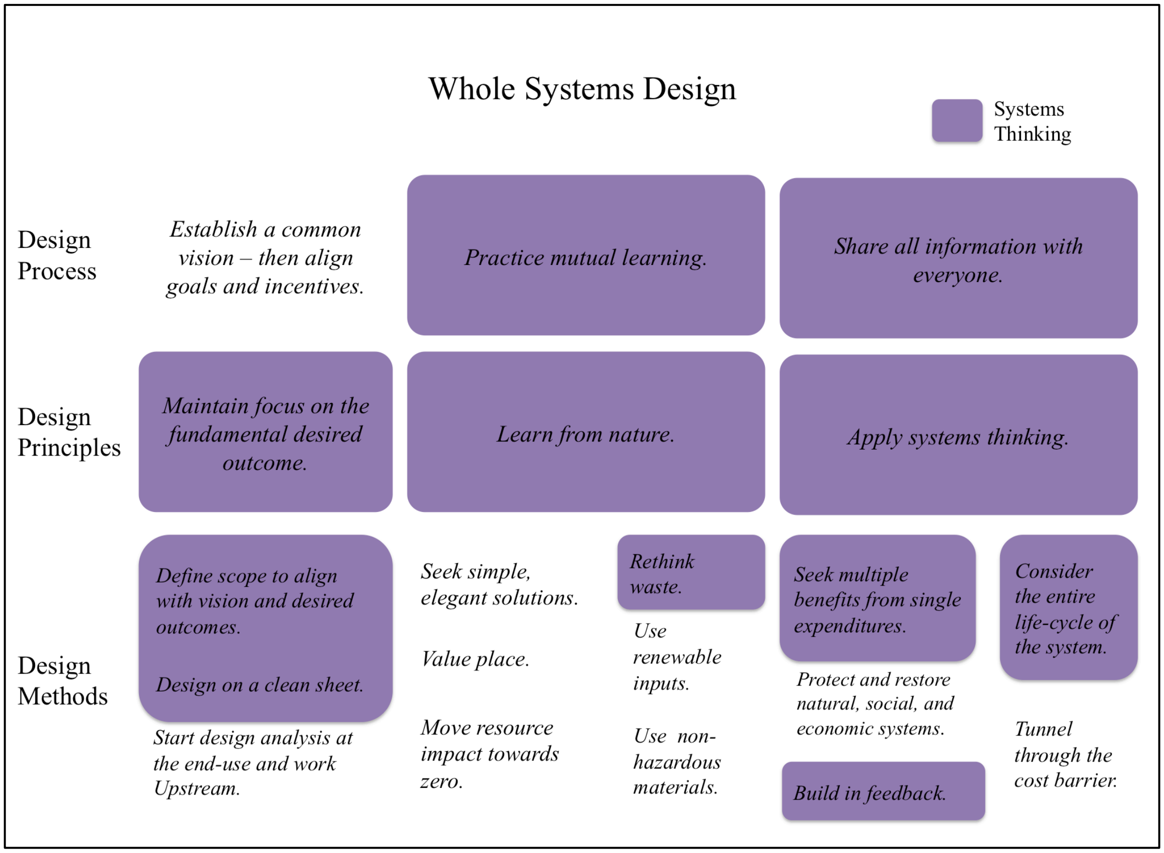

Figure 7: Components of Framework Found in Systems Thinking Sources

The components of the framework identified by the five environmental management and business resources are shown in Figure **8**. As expected, these sources focused their attention on the reduction of waste and minimization of resource use. These elements are good business practice because they reduce costs and in turn boost profits. Interestingly, the environmental management and business related sources failed to identify any of the design methods related to the beginning of the design process:

defining the scope to align with vision and desired outcomes, designing on a clean sheet, and starting design analysis at end-use and work upstream. This was most likely because the audience for these types of principles is management and not individuals that necessarily design.

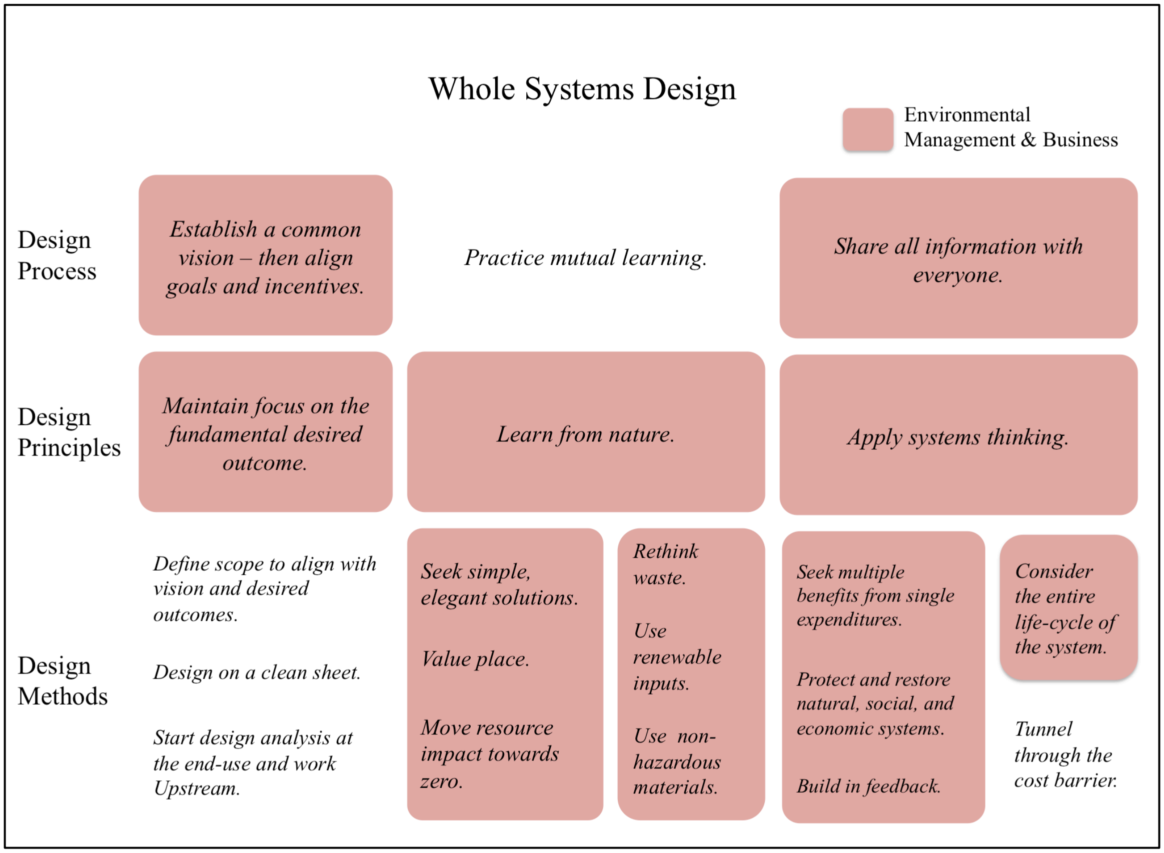

Figure 8: Components of Framework Found in Environmental Management & Business Sources

The frequency of sources from each category for each component of the design framework is shown in Figure **9**. The most commonly cited component of the framework was the design method: move resource impact towards zero. A total of 26 sources in every category, with systems thinking being the only exception cited this as a design principle. Designers can move their resource impact towards zero by minimizing the demand for resources while maximizing the efficiency of resources used over the entire life cycle of the solution (Gagnon et al, 2009; Lovins et al., 2010; Lovins et al, 1999). The next most commonly cited component, with 24 sources recognizing it, was the design method: rethink waste. This principle requires designers to radically re-evaluate the concept of waste. As suggested by William McDonough waste is food. The waste of one process or component can become the food or input for another part of the system so that the entire system can shift towards zero waste (Benyus, 1998; Holmgren, 2002; Lovins et al, 1999).

Another interesting distribution of sources was for the design method: value place. Valuing place means to understand, respect, and integrate when possible the local culture, geography, values, and history into the design. This element of the design framework was recognized as an essential element to sustainable design by 20 sources, of which mostly fell under the field of architecture, planning, and urban design. Eleven of the fourteen architecture sources emphasized the importance of valuing place in sustainable design, where only five of the nineteen engineering sources did so. This was somewhat expected, because engineers are not known for their social design considerations to the extent that architects, planners, and urban designers are. Half of the sustainable development sources, and one of the sustainable management and business sources mentioned valuing place as a principle to follow.

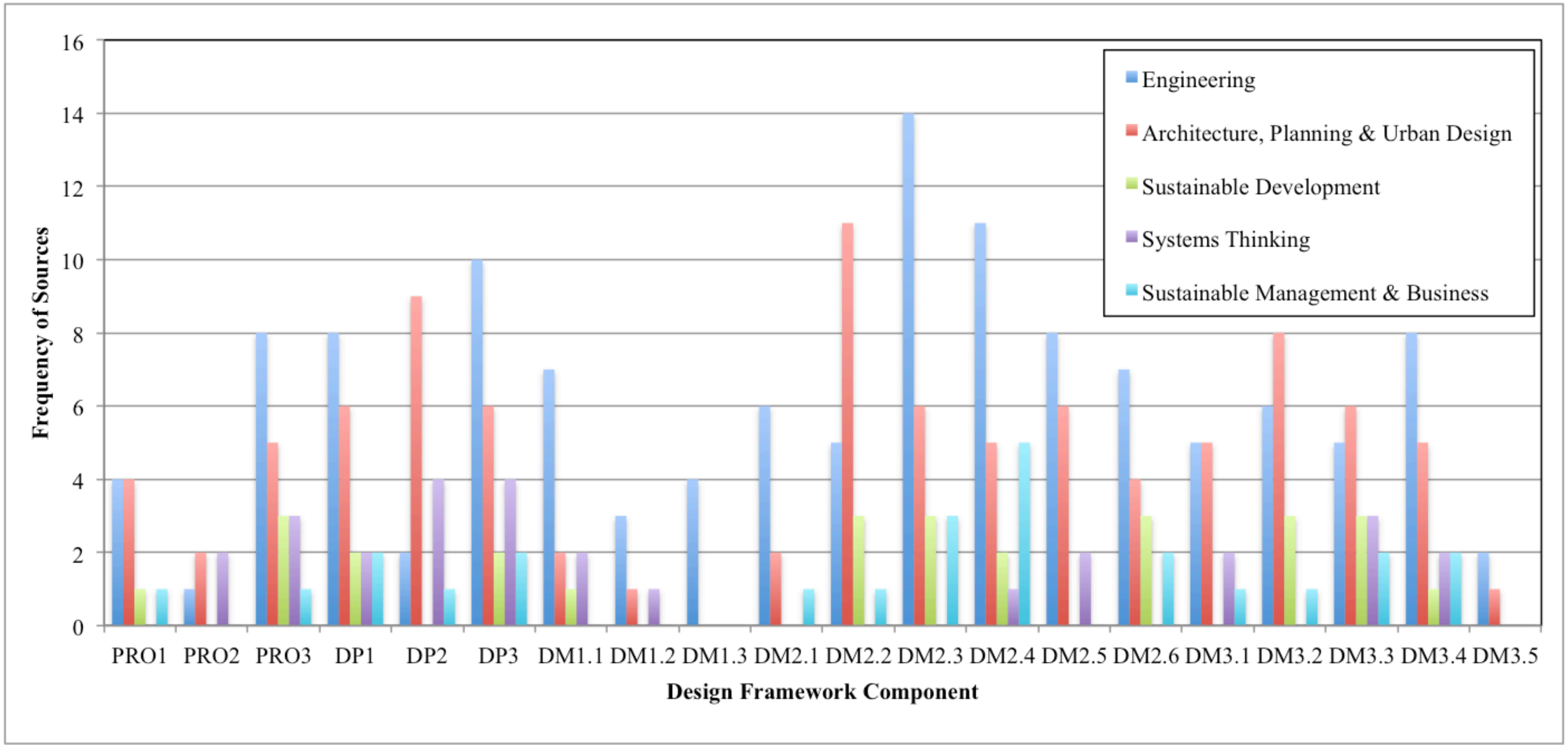

Figure 9: Distribution of Sources for Each Component of Framework

CHAPTER FOUR: SUMMARY, CONCLUSIONS

"What is the use of living, if it be not to strive for noble causes and to make this muddled world a better place for those who will live in it after we are gone?"

- Winston Churchill

The conclusions of this study are arranged within this chapter. This chapter summarizes the research presented, acknowledges implications and limitations of this research, and proposes topics for future research.

4.1. Summary

As afore mentioned the problems we face as designers, and as a society are indisputably significant. Shortages of energy, natural resources, water, and food; threats of war, and political instability; rising levels of poverty, homelessness, and disease; slipping quality of education and infrastructure; all of these things are compounded by what is arguably our largest issue, radical population growth. Engineers, designers, and policy makers will need to rise to these challenges with radically creative solutions, and they must do so under the constraints of social, economic, and environmental sustainability. One approach to design that has the potential to lead to transformational solutions is whole systems design, but it's guiding principles and processes have remained poorly defined. Defining the principles of whole systems design is a crucial step in advancing its applicability in sustainable design. To address this need, this research posed two questions:

1. What are the guiding principles of sustainable design as defined by engineering and related design disciplines (e.g. architecture, planning)?

2. How can these individual principles be integrated into a holistic set of design principles, termed whole systems design, that is applicable for sustainable design across all disciplines?

The objective of this research then was to discover and organize the design framework that defined sustainable whole systems design. Using a systematic literature review, 501 principles related to sustainable design from five different sustainable design categories were identified. Through concept mapping techniques, these 501 principles were coded and organized into a unified framework for whole systems design. The framework consisted of three categories and 20 elements or principles. The principles were arranged into categories that described the processes, principles, and methods of whole systems design. Several key findings from the literature review and subsequent framework were:

- There were many common elements of the whole systems design framework identified by the different design disciplines.
- The elements of the design framework considered social, economic, and environmental facets of sustainable design.
- Very few engineering sources identified social considerations (for example valuing place, i.e. the local culture, customs, community, and geography of a place) of design as essential principals. By considering different design disciplines, this framework was able to address this type of weakness in design theory.
- The most commonly cited element of the framework was focused on moving the resource impact of the design towards zero.

The primary reasons for conducting a systematic literature review are to: summarize the existing literature around a subject, identify gaps in current research and suggest future research, and provide a framework or background to position future research. A principal reason this research employed a literature review was to provide a framework or background to position future research on whole systems design. Defining whole systems design in a way that demonstrates unanimity between design disciplines builds a platform for designers to agree upon and also allows for future research on the process of whole systems design.

Clarifying the principles and framework of whole systems design and identifying effective methods to incorporate these principles into engineering education will help students postulate solutions for more sustainable infrastructure design. This research is an essential step to advancing the use of the process by designers. Whole systems design has the chance to help current and future designers produce solutions that efficiently address the ecological, social, and economic demands of the system as a whole, a key to building a more socially, economically, and environmentally sustainable future. Adapting these principles specifically for the design of sustainable cities and green infrastructure, and validating the principles are the next logical steps for this project.

4.2. Implications

- The research surrounding whole systems design was synthesized and organized into one document making it easier for future researchers to find literature on whole systems design. Organizing the literature has laid an essential foundation for future research in the field of sustainable and whole systems design to build from.

- The shared framework elements amongst the five different categories indicate that a unified broad design framework is possible. The commonalities also indicate that consensus exists and successful interdisciplinary collaboration on projects is feasible.
- The principles of whole systems design identified in this literature review systematically organized the current body of knowledge surrounding sustainable design and holistic thinking into one coherent report and framework. Organizing the literature and defining the principles directly addresses the ambiguity about what whole systems design is which designers and literature have identified as one of the reasons it is difficult to practice. The elements of the design framework were worded and defined in a simple and universal manner to make them germane for both academia and practicing designers in multiple fields.
- Including design principles from multiple disciplines, perspectives, and experts broadens the applicability and mitigates the bias of the principles identified in the literature review.
- A broad framework for whole systems design that is applicable across types of design and a variety of disciplines is essential for the interdisciplinary collaboration necessary to find sustainable solutions to the global and local issues such as energy, water, and education. Designers from different fields must realize that they share many similar ideals and that many of the differences are often a matter of semantics. The broad framework demonstrates consensus amongst the different fields of design will put designers onto the same page and promote a more synergistic mindset. But the framework also reveals that each field has a

unique perspective to bring to the design table by highlighting the differences between the design disciplines.

4.3. Limitations

The following limitations of this research should be considered:

- Time: Only so much time could be spent conducting the literature review. Additional time would have allowed for additional sources to be included.
- Data Extraction: Only one researcher coding and categorizing the original sources. It would have been preferable to have more than one coder. However, multiple people mapped the codes to shape the framework and organization of the codes.
- Limited Sources of Data: The literature specifically addressing whole systems design is limited. The topic is in its infancy, and therefore required related design disciplines to be investigated. However, broadening the scope of literature considered is also one of the strengths of this research.

4.4. Future Research

Future research should focus on:

- Validating the design framework and seeking expert input on the principles, processes, and methods of whole systems design by this research. The next phase of this research project will seek expert input and student input about the elements of the design framework to identify gaps and also to build consensus. The experts and students should be given the opportunity to organize the elements through concept mapping software.

- Identifying whether students have natural inclination for systems thinking. Now that whole systems design has been defined, it is now appropriate to try to measure its characteristics. Systems thinking and the ability to see the interrelatedness of individual parts has been identified in previous research and this research as part of the whole systems design process. Therefore, identifying the ability of designers and students to think systemically could be a strong indicator of whether they will be successful at implementing this design paradigm.

  Understanding how to develop students and designers into systems thinkers. If designers and students are lacking systems thinking skills it will be essential to find effective ways to develop their skills to improve their success at using the whole systems design process.
- Finding effective methods for teaching the framework and principles to both students and practicing designers. Now that principles, processes, and methods of whole systems design have been identified through an extensive literature review, the next task becomes how to integrate the findings into design education. A variety of pedagogies should be investigated, especially interactive and problem based approaches that allow students to work with the elements of whole systems design rather than simply memorize content.
- Developing tools to guide designers through the whole systems design process. The process of whole systems design has been identified in previous research as counterintuitive and not without its difficulties. Developing tools to help designers collaborate, think non-linearly, and challenge their past mental models will be essential to furthering the use and success of the whole systems design

process. Tools that also aid designers in the quantitative aspects of whole systems design should be developed, i.e. life-cycle tools, modeling tools, which use a systems approach.

- Measuring the effectiveness of whole systems design in furthering ecologic, economic, and social sustainability goals will be an avenue for future research. Comparing the outcomes of design initiatives achieved using whole systems design with traditional linear design approaches will demonstrate its need to be the "norm" in the design world.

4.5. Concluding Remarks

Rising to local and global challenges of energy, water, food, poverty, educational gaps, and environmental degradation will require a drastic change in the way we design our world. We can no longer ignore the interrelatedness of the systems in our world. These issues are intertwined, and the solutions designers and engineers dream up will have to recognize and consider that fact. Whole systems design is one approach that offers designers the opportunity to holistically optimize solutions for social, environmental, and economic sustainability. However, it has remained largely undefined and it's principles ambiguous making it a difficult design paradigm to implement.

This research addressed this issue by expanding the boundaries of the literature to incorporate other more widely accepted and known principles of sustainable development, engineering, and design. In this way, this literature review highlighted commonalities to build consensus and illuminated differences to fill in gaps to create a framework that can help designers meet the challenges of sustainable design.

The development of a broad framework for whole systems design rather than tailoring a framework for each individual field of design is essential to creating a synergistic mindset amongst design teams. This research demonstrated that different fields of design have been talking about the same things, and from this realization designers can begin to find common ground with one another. However, the framework also showed that each field brings a unique perspective to the table, and that when combined, a holistic approach, and in turn a more holistic sustainable solutions are possible. Combining the theories, perspectives, and practices of multiple design disciplines and experts created a design framework germane for applications of design ranging from the microscopic level of a chemical, to the macroscopic level of a city.

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APPENDICES

APPENDIX A: LITERATURE REVIEW PROTOCOL

Rationale for Review

Aristotle theorized, "The whole is more than the sum of its parts." Design engineers often overlook this simple philosophy. We employ a reductionist approach when designing the built environment: engineering solutions for the individual parts rather than the system as a whole, creating and exacerbating problems in the process. A whole-systems interdisciplinary approach that considers the interrelatedness of global issues is increasingly recognized as essential to finding truly sustainable engineering solutions (NSB 2007). However, the precise nature of this whole-systems approach to sustainable design remains undefined. This literature review intends to systematically synthesize the multiple variations of the principles of sustainable design and engineering into one holistic set of principles (whole-systems design) that emphasizes systems thinking.

Research Questions

1. What are the guiding principles of sustainable design as defined by engineering and related (e.g. architecture, planning) disciplines?
2. What are the guiding principles of systems thinking?
3. How can these principles be integrated into a holistic set of design principles, whole-systems design that can be used by all designers.

Search Strategy

Search Terms:

- Broad Design Terms
  - Whole Systems Design Principles
  - Whole Systems Thinking Principles
  - Whole Systems Approach
  - Sustainable Design Principles
  - Green Design Principles
  - Ecological Design (Eco-Design) Principles
  - Integrated Design Principles
  - Cradle to Cradle Design Principles
  - Sustainable Development Principles
  - Sustainable Engineering Principles
  - Green Engineering Principles
  - Design for the Environment
  - Biomimicry Design Principles

Resources:

- Databases
  - Google Scholar
  - Science Direct
- Textbooks
  - Identify through library search, Google Scholar, and Amazon?
- Reference Lists from Review Articles
- Conference Proceedings

        - From Google Scholar Search
    - Reports

Documenting The Search:
As the search is conducted fill out the search documentation excel sheet, and save articles appropriately.

Selection Criteria and Procedures
Study Selection Criteria
The studies should focus on and identify elements, principles, or frameworks for sustainable design, or the other search terms mentioned above. The resources should be broad and focus on principles rather than applications.

Study Selection Process

4. Identify articles and publications through search strategies using established search terms.
5. Read the title, abstract, and key words to see if it is applicable to answering these research questions.
6. If applicable, read full article, or skim publication for relevant chapters and use selection criteria to determine if the article should be included.

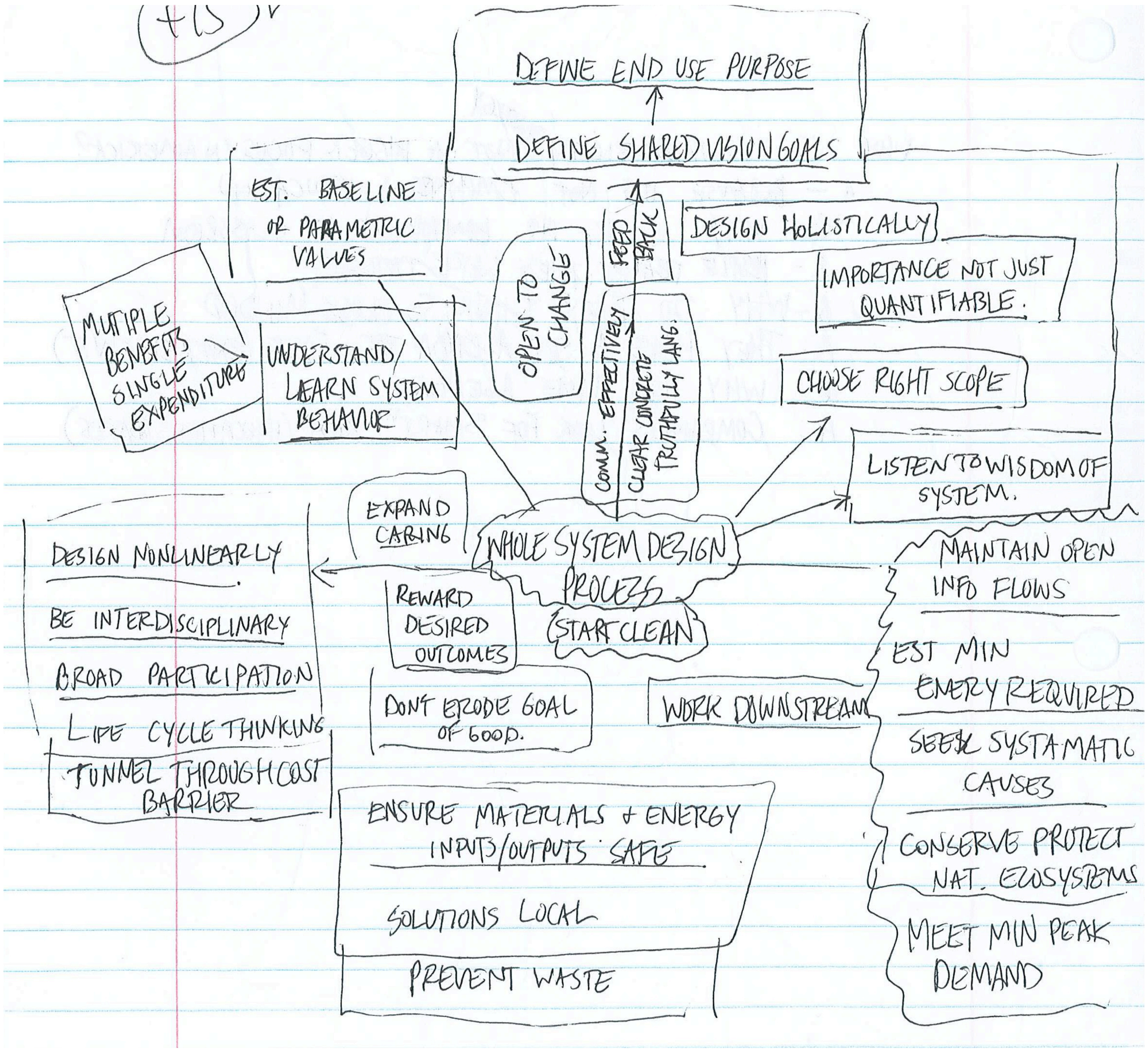
Quality Assessment Checklists and Procedures
Use the quality assessment worksheet to quantify and assess the quality of each work. As the literature review is conducted, the quality assessment measures can be adjusted to better assess the quality of each source. Any changes that are made will require previously assessed articles/sources to be reevaluated based upon the new measures.

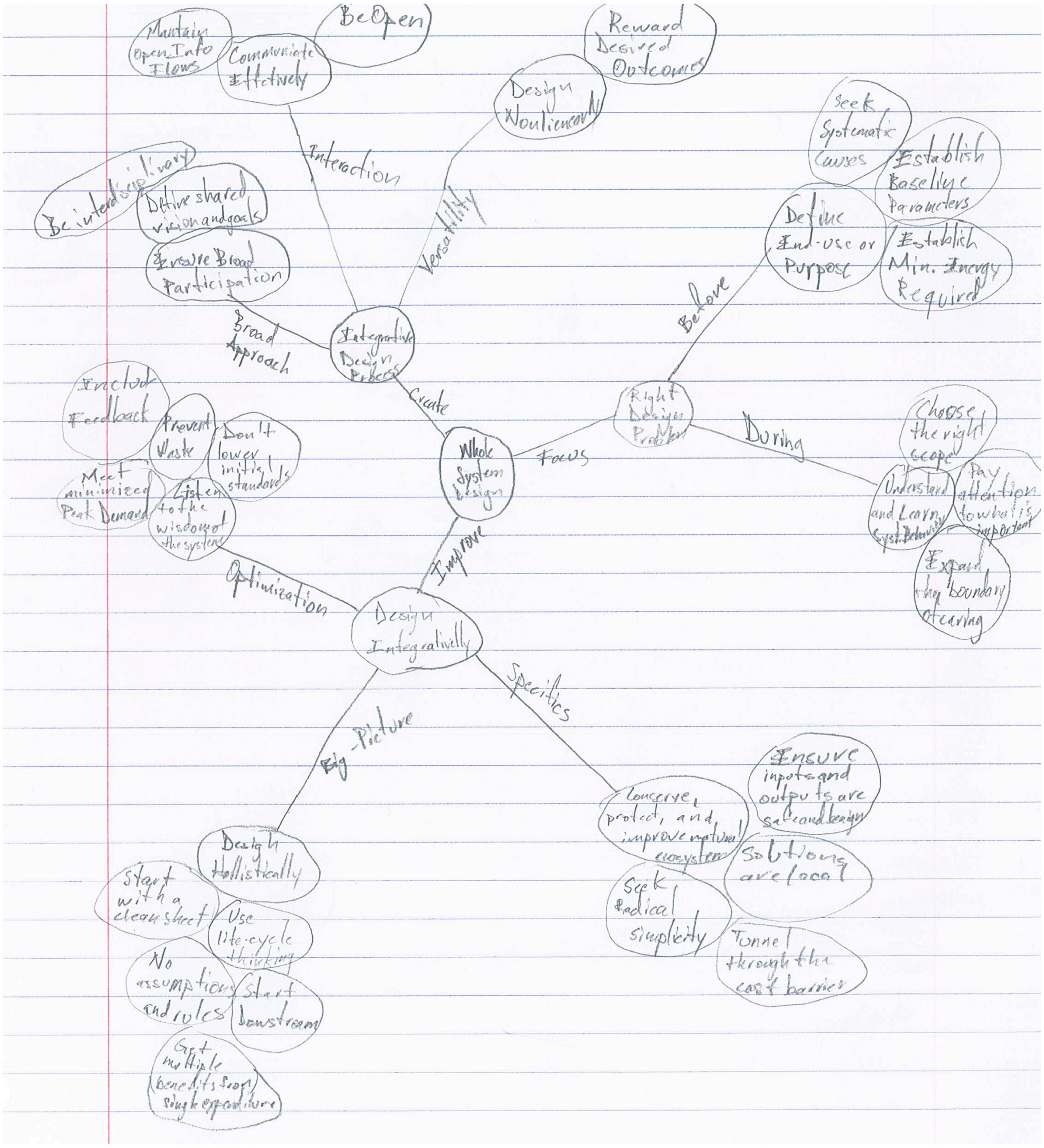
Data Extraction Strategy
Each article that meets the quality assessment criteria will be read to extract principles for whole-systems design. Principles may be in the form of lists, figures, tables, charts, or summarized/extracted from text. The original wording will be maintained for data extraction. During synthesis, the principles will be coded and grouped and reworded.

Synthesis of Extracted Data
The principles extracted from the articles and other sources will be coded and categorized into appropriate themes. The themes will then be arranged to form a framework, or guiding principles to whole-systems design.

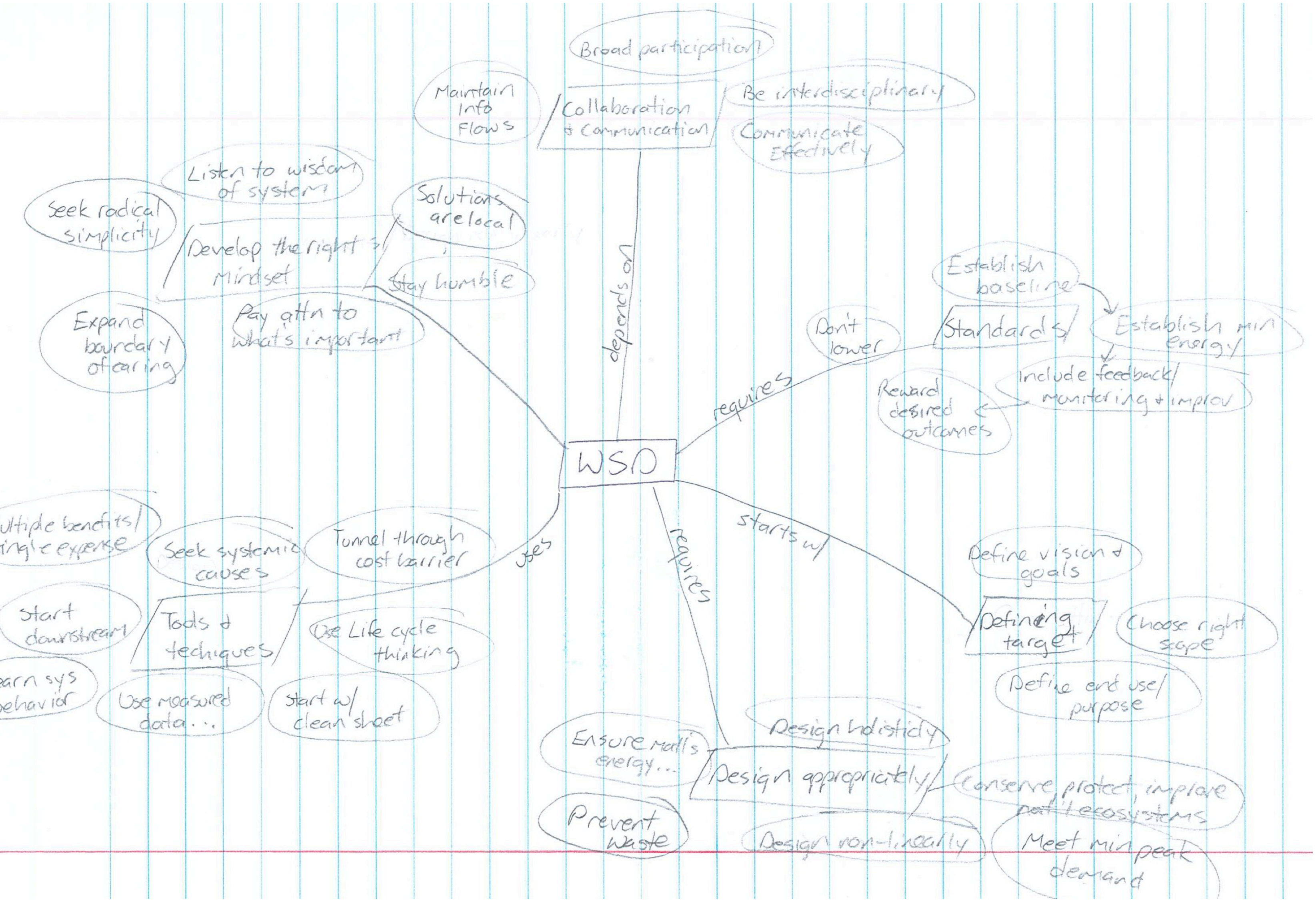
Project Timetable
9/1/2010-12/1/2010: Preliminary Review/Survey of the Literature
12/2/2010-12/25/2010: Develop Literature Review Protocol
12/26/2010-1/5/2010: Search for Literature & Select Appropriate Sources
1/5/2010-2/5/2010: Read & Extract Data from Literature
1/20/2010-3/1/2010: Synthesize Data
3/1/2010-4/15/2010: Draw Conclusions & Complete Thesis

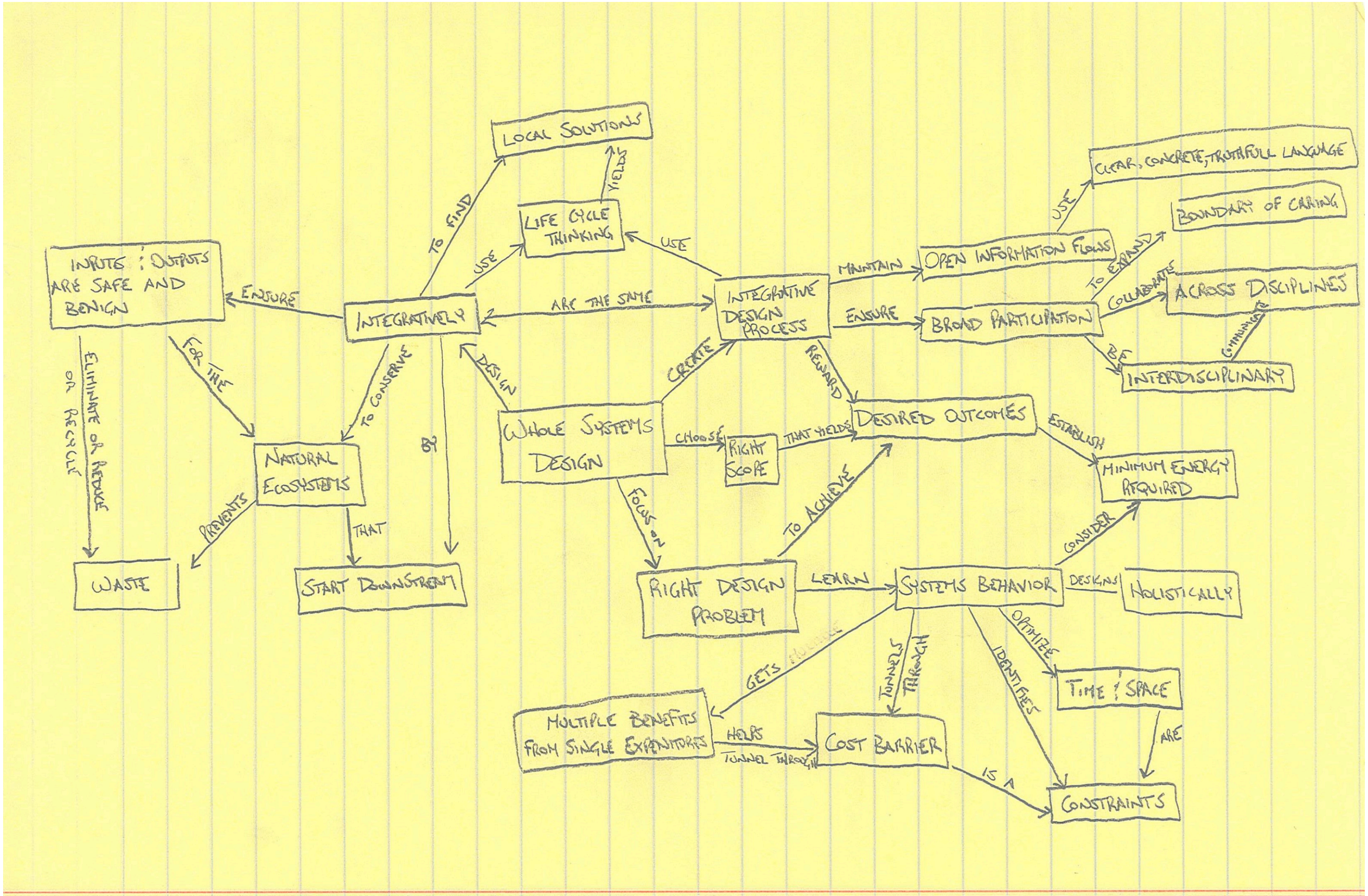
APPENDIX B: SAMPLE STUDENT CONCEPT MAPS




Whole System Design
Create
Integrative Design Process
Interaction
Communicate Effectively
Maintain Open Info Flows
Be Open
Versatility
Design Nonlinearly
Reward Desired Outcomes
Broad Approach
Ensure Broad Participation
Define shared vision and goals
Be interdisciplinary
Focus
Right Design Problem
Before
Define End-use or Purpose
Seek Systematic Causes
Establish Baseline Parameters
Establish Min. Energy Required
During
Choose the right scope
Understand and Learn System Behavior
Pay attention to what is important
Expand the boundary of caring
Improve
Design Integratively
Optimization
Include Feedback
Prevent Waste
Don't lower initial standards
Meet minimized Peak Demand
Listen to the wisdom of the system
Big-Picture
Design Holistically
Start with a clean sheet
Use life-cycle thinking
No assumptions and rules
Start Downstream
Get multiple benefits from single expenditure
Specifics
Conserve, protect, and improve natural ecosystem
Ensure inputs and outputs are safe and benign
Solutions are local
Seek radical simplicity
Tunnel through the cost barrier

SCOTT STANTON




LOCAL SOLUTIONS
LIFE CYCLE THINKING
YIELDS
TO FIND
USE
USE
INPUTS & OUTPUTS ARE SAFE AND BENIGN
ENSURE
INTEGRATIVELY
ARE THE SAME
INTEGRATIVE DESIGN PROCESS
MAINTAIN
OPEN INFORMATION FLOWS
USE
CLEAR, CONCRETE, TRUTHFULL LANGUAGE
TO EXPAND
BOUNDARY OF CARING
COLLABORATE
ACROSS DISCIPLINES
ENSURE
BROAD PARTICIPATION
BE
INTERDISCIPLINARY
COMMUNICATE
ELIMINATE OR REDUCE OR RECYCLE
FOR THE
TO CONSERVE
BY
DESIGN
CREATE
REWARD
NATURAL ECOSYSTEMS
WHOLE SYSTEMS DESIGN
CHOOSE
RIGHT SCOPE
THAT YIELDS
DESIRED OUTCOMES
ESTABLISH
MINIMUM ENERGY REQUIRED
PREVENTS
THAT
WASTE
START DOWNSTREAM
FOCUS ON
TO ACHIEVE
CONSIDER
RIGHT DESIGN PROBLEM
LEARN
SYSTEMS BEHAVIOR
DESIGNS
HOLISTICALLY
GETS
TUNNELS THROUGH
IDENTIFIES
OPTIMIZE
TIME & SPACE
MULTIPLE BENEFITS FROM SINGLE EXPENDITURES
HELPS TUNNEL THROUGH
COST BARRIER
IS A
ARE
CONSTRAINTS