# *A framework for sustainable whole systems design*

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*A whole systems approach, considering the interrelatedness of both problems and solutions, can help create more sustainable designs. Still, designers often apply exclusively reductionist approaches to generate designs. One way to address this issue is to reduce ambiguity in the whole systems approach. This paper describes research to define and unify elements of whole systems design. Elements were identified through a methodical review of sources describing theories, perspectives, and practices from multiple design disciplines. These elements were coded and then organized using concept mapping. The resulting framework has 20 elements categorized as processes, principles, and methods. This framework is meant to help enable more widespread application of whole systems design in practice.*
*Published by Elsevier Ltd.*

*Keywords: sustainable design, systems design, design model, design methods, design theory*

The challenges we face as a society, and therefore as designers, are significant. These challenges include shortages of energy, natural resources, water, and food; war and political instability; rising levels of poverty, homelessness, and disease; and slipping quality of education and infrastructure. At the same time, current world population is around 7 billion and is projected to reach 10.1 billion by 2100 (Kaiser, 2011). Rapid population expansion accelerates the strain on natural resources and energy, magnifying the impact we have on the health of the planet that supports us.

Carbon footprint is one way to illustrate humans' impact on the environment. It is quantified by converting our use of fossil fuels (e.g. for electricity, heating, and transportation) to metric tons of carbon dioxide emissions (Carbon Footprint, 2011). Carbon footprint is associated particularly with the issue of climate change; the higher the carbon footprint, the larger the contribution to global climate change. There is a worldwide target to combat climate change of 2 metric tons per person per year (Carbon Footprint, 2011). Worldwide, we are twice as high as this target. In the U.S., we are ten times as high (Massachusetts Institute of Technology [MIT], 2008). Carbon emissions are

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www.elsevier.com/locate/destud
0142-694X $ - see front matter *Design Studies* **33** (2012) 456–479
doi:10.1016/j.destud.2012.03.001
Published by Elsevier Ltd.

just one example that our current trajectory is not sustainable, which will negatively impact the ability of future generations to meet their needs.

Yet, sustainability is not just about future generations. Many people alive today are unable to meet their own needs. Three in every four people residing in rural areas in developing countries are living on less than a dollar a day and suffering from malnutrition. In 2005, one in three urban dwellers (approximately 1 billion people) were living in slum conditions (UN, 2007). The challenges extend beyond poverty 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 were girls (UN, 2007).

Addressing these challenges requires changes in how we design our world. We must consider the interrelatedness of systems. The problems we face are intertwined and effective design solutions will have to account for this reality. For example, consider an engineer tasked with alleviating congestion on a city road. Guided by traditional design theory, they would consider adding more travel lanes, or constructing a new street through an existing neighborhood. However, this reductionist approach can be ineffective or even have the opposite effect of its original intent. Adding a new lane of traffic or building a new road can make travel more convenient, which can increase automobile traffic, meaning traffic conditions further deteriorate. Building new streets for automobiles can harm neighborhood connectivity and local businesses, and also lead to more air and water pollution. A more holistic approach to the problem may consider ways to reduce the number of personal automobiles on the road perhaps by reducing travel lane width and adding accommodations for pedestrians, bikes and mass transit. Measures like these have been shown to reduce or handle current traffic patterns, while improving the safety, walkability, and economic vitality of neighborhoods (National Complete Streets Coalition, 2011). Of course, this may not be the solution for every situation, but examples like this show that solutions are possible. To create them, we will have to break down silos, work across disciplines and change our perspectives.

Whole systems design is one approach to sustainable design offering great potential, however the processes, principles, and methods guiding the whole systems approach are not clearly defined or understood by practicing designers or design educators (Charnley, Lemon, & Evans, 2010; NSB, 2007). The Rocky Mountain Institute (RMI) discusses whole systems design as follows:

> "*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" (Lovins et al., 2010, p. 7).

For this study, RMI's discussion has been adapted to a definition for whole systems design that is broadly applicable across design disciplines:

> "Whole systems design considers an entire system as a whole from multiple perspectives to understand how its 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 field of whole systems design is still young, and the literature surrounding it remains limited (Coley, 2009). Ambiguity leads to difficulty implementing the whole systems design process (Charnley et al., 2010). Admittedly, the definition, principles, and processes of design itself are open to multiple interpretations. Still, highlighting commonalities and considering multiple perspectives of sustainable design theory can help build consensus. Thoughtful observation of differences in design theory can also help fill in missing pieces to develop a more holistic design philosophy. This research aims to build a more complete definition of whole systems design, its guiding principles, and its process by systematically surveying a broad scope of sustainable design literature. Whole systems design does not guarantee sustainable design outcomes. It may, however, offer more opportunity than traditional design approaches for designers to create sustainable solutions to our most pressing issues.

Charnley et al. (2010) concluded from their analysis of multiple case studies attempting to implement whole systems design 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, a key factor in the success of the cases studied was the project teams' "understanding of purpose and process." Despite the need and possible benefits, a common understanding of sustainable whole systems design does not exist. The authors of principles of green engineering contend 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 (Anastas & Zimmerman, 2003)."

Yet these principles of green engineering, initiated by chemical engineers, seem to emphasize or favor the molecular scale. The Rocky Mountain Institute has developed Factor Ten Engineering (10xE) principles that embody whole systems thinking and integrated design. This approach is more broadly applicable across scales than the principles of green engineering, but is heavily focused on energy, which is just one of many sustainability issues.

The literature discussing whole systems design demonstrates a need to better define and develop this design paradigm. This research is not a direct response to any one set of existing principles, but rather is intended to systematically merge them to find common ground among the design disciplines to develop a more complete and applicable framework for design. This research highlights commonalities to build consensus and illuminates differences to fill in gaps and build a framework that can help designers meet the challenges of sustainable design.

Specifically, this research aimed to answer the following questions:

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

Answering these research questions will define the processes, principles, and methods of whole systems design from the perspective of multiple design disciplines. A better understanding of whole systems design could lead to more sustainable design solutions to the interconnected worldwide challenges we face.

# 1 Methods

To answer our first research question, a systematic literature review was performed. Systematic literature reviews are conducted primarily to: summarize the existing literature around a subject, identify gaps in current research, and provide a framework or background to position future research. For this application, the systematic literature review will show overlap between design disciplines and provide a framework to position future research on whole systems design. As adapted from an established review method, the literature review included three stages as shown in Figure 1: (1) planning the review, (2) conducting the review, and (3) reporting the review (Kitchenham, 2004).

The *need for the review* was described in the previous section. During the planning phase of the review, a review protocol was developed outlining: 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. These elements of the review protocol are described in more detail in the following sections.

Resources were identified beginning with databases (e.g. Google Scholar and Science Direct) and followed up with reference lists from relevant articles,

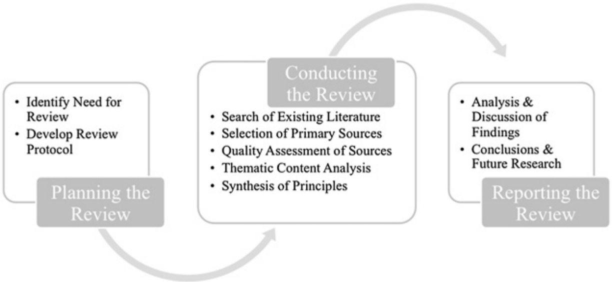


*Figure 1 Systematic literature review process*

books, and reports. To bind 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 gained more widespread use (Brundtland, 1987). 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.

The search strategy involved 13 of the most common and broad search terms spanning the engineering, architecture, and planning disciplines pertaining to sustainable design. Narrow sustainable design terms and fields were not included in the search strategy to maintain focus on just the most relevant resources. For example the term "complete streets," was not included in the search, because this would have required the researchers to include narrow terms from other design disciplines such as "lean production" from mechanical engineering design. However search terms that applied to multiple design fields were used such as "whole system design" or "green design." Search terms were: 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; and Biomimicry principles.

The terms selected for the review were identified through an initial search process of sustainable design and whole systems design literature. The first iteration of the database literature search was conducted from January 5, 2011 through January 19, 2011. Upon completion of this first round of the literature search, the articles identified were reviewed along with additional sources identified in the references of selected articles.

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 processes, principles, and methods 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; and (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.

For example, the article, "Design Through the 12 Principles of Green Engineering" by Anastas and Zimmerman (2003) was included as a primary source in the review because it outlined specific principles of green engineering. On the other hand, articles focusing on *applications* of green engineering principles, such as Zhao's, "Innovative Applications of Ionic Liquids As 'Green' Engineering Liquids," were not included as primary sources in the review. In all 49 sources were selected for inclusion in this study shown in Table 1.

A quality assessment checklist with defined criteria was used to assess the value of the 49 selected resources. The criteria included: type of source, name of journal (if applicable), scale of sustainability (molecular, product, process, or system), peer reviewed (yes or no), field of authors, years of experience, and number and field of citations. 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 elements of whole systems design based upon the definition set forth at the beginning of the study. The elements could be in the form of figures, lists, tables, charts, or summarized from the text. The original wording of the elements was maintained during the extraction process and included in the literature review excel database. Elements extracted from resources were empirically coded and categorized into appropriate themes. Coding occurred in three iterations. A list of all the extracted elements 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 elements and assigned codes to elements that matched the initial coding list. Take for example, some of the sources that were categorized under code C14 – which was *learn from nature*:

> 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."

**Table 1 Articles selected for inclusion in study**

| *Source #* | *Source code* | *Source title* |
|---|---|---|
| 1 | E1 | RMI's 10XE Principles (Lovins et al., 2010, p. 7) |
| 2 | E2 | Natural Edge WSD Suite (TNEP Engineering Sustainable Solutions Program – Whole Systems Design, n.d.) |
| 3 | S1 | Thinking in Systems - Chapter 7 (Meadows, 2008) |
| 4 | A1 | The Hanover Principles (McDonough & Braungart, 1992) |
| 5 | E3 | EPA's Principles of Green Engineering (EPA, 2010) |
| 6 | SD1 | The Bellagio Principles (IISD, 1996) |
| 7 | S2 | The Butterfly Effect' Creative Sustainable Design Solutions through Systems Thinking" - A Taxonomy for Systems Design (McMahon & Hadfield, 2007, p. 247) |
| 8 | SD2 | The Natural Step (The Four System Conditions, 1991) |
| 9 | A2 | Wilderness Values from Gentle Architecture (Wells, 1981) |
| 10 | A3 | Ecological Design (Ryn, Van, & Cowan, 2007) |
| 11 | E4 | Design Through the 12 Principles of Green Engineering (Anastas & Zimmerman, 2003) |
| 12 | A4 | HOK Guidebook to Sustainable Design - Sustainable Design Goals (Mendler, Odell, & Lazarus, 2006) |
| 13 | A5 | The 10 Melbourne Principles (UNEP, 2002) |
| 14 | A6 | Planning for Sustainability - Elements of the Sustainability Planning Approach (Wheeler, 2004) |
| 15 | E5 | Sustainable Development in Engineering: A Review of Principles and Definition of a Conceptual Framework for Sustainability in Engineering (Gagnon, Leduc, & Savard, 2009) |
| 16 | E6 | Design for Sustainability (DfS) - The Interface of Sustainable Production and Consumption - SCALES Core Principles (Spangenberg, Fuad Luke, & Blincoe, 2010) |
| 17 | A7 | Six Biophilic Design Element (Kellert, 2008) |
| 18 | E7 | Biomimicry: Innovations Inspired by Nature (Benyus, 1998) |
| 19 | E8 | Design Principles for Ecological Engineering (Bergen, Bolton, & Fridley, 2001) |
| 20 | A8 | The Philosophy of Sustainable Design (McLennan, 2004) |
| 21 | A9 | From Ecocities to Living Machines: Principles of Ecological Design (Todd, 1994) |
| 22 | A10 | Principles and Practices of Ecological Design (Shu-Yang, Freedman, & Cote, 2004) |
| 23 | SD3 | Sustainable Cities: The Sanborn Principles for Sustainable Development (Lovins et al., 1994) |
| 24 | A11 | Permaculture: Principles & Pathways Beyond Sustainability (Holmgren, 2002) |
| 25 | E9 | Ecological Engineering and Ecosystem Restoration (Mitsch, 2004) |
| 26 | A12 | City Building: Nine Planning Principles for the Twenty-first Century (Kriken, 2010) |
| 27 | E10 | Applying the Principles of Green Engineering to Cradle to Cradle Design (McDonough, Braungart, Anastas, & Zimmerman, 2003) |
| 28 | M1 | CERES Principles (Ceres Principles, 1989) |
| 29 | A13 | Ahwahnee Principles (Calthorpe et al., 1991) |
| 30 | E11 | A Compilation of Design for Environment Principles and Guidelines (Telenko, Seepersad, & Webber, 2008) |
| 32 | E12 | 12 Principles of Engineering for Sustainable Development Endorsed by Royal Academy of Engineers (Dodds & Venables, 2005) |
| 33 | SD4 | Earth Charter Principles (The Earth Charter, 2000) |

Table 1 (*continued*)

| *Source #* | *Source code* | *Source title* |
|---|---|---|
| 34 | SD5 | The Daly Principles (Daly, 1991) |
| 35 | E13 | Sustainability Principles and Practice for Engineers (Boyle & Coates, 2005) |
| 36 | E14 | Inherently Safer Design (García-Serna, Pérez-Barrigón, & Cocero, 2007) |
| 37 | E15 | Materials selection and design for development of sustainable products - Guidelines for Sustainable Product Design (Ljungberg, 2007) |
| 38 | M2 | Four ecosystem principles for an industrial ecosystem (Korhonen, 2001) |
| 39 | E16 | EcoDesign and The 10 Golden Rules (Luttropp & Lagerstedt, 2006) |
| 40 | E17 | Industrial Ecology – A Framework for Product and Process Design – Hardin Tibbs Framework (Ehrenfeld, 1997) |
| 41 | E18 | Environmentally Sensitive Design - Leonardo Was Right! "Principles of Design for Disassembly" (Thompson, 1999) |
| 42 | M3 | Eco-Efficiency and SME's in Nova Scotia, Canada - Elements of Eco-Efficiency (Cote, Booth, & Louis, 2006) |
| 43 | M4 | Environmental Principles Applicable to Supply Chains Design and Operation (Tsoulfas & Pappis, 2006) |
| 44 | SD6 | Achieving Sustainable Development (Jacobs, 1985) |
| 45 | M5 | A Roadmap to Natural Capitalism (Lovins, Lovins, & Hawken, 1999, p. 16) |
| 46 | S3 | 12 Living System Principles (Sweeney, n.d) |
| 47 | S4 | 12 Habits of Mind (Sweeney, n.d) |
| 48 | A14 | Integrated Design MITHUN – Principles (Macaulay, 2008) |
| 49 | E19 | 12 Principles of Green Chemistry (Anastas, 2000, p.30) |

The above principle was coded under C14 – *learn from nature* because it referred to nature as a mentor, or something to be learned from and essentially mimicked. Like Hanover principle 8, Melbourne principle 5 instructs designers to mimic nature's ecosystems in design of cities, i.e. learn from nature and build a model in its image.

> 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."

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 from the Ahwahnee Principles, "As many activities as possible should be located within easy walking distance to transit stops."

> Principle 4 from the Ahwahnee Principles, "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."

These two Ahwahnee Principles are very specific to community planning, and while valuable principles, they are not directly applicable to multiple types of design, and were therefore not coded. Elements that did not fit under the initial coding list were analyzed further to discover common threads and ideas, which became additional codes used in subsequent coding iterations. The first version of the coding list contained twenty-nine codes or themes. The finalized list of codes is provided in Table 2. 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. Concept mapping is a way to visually represent the relationships between ideas, images, and words. Processes like concept mapping are used in many disciplines 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).

Concept mapping was particularly appropriate because these maps reveal connections and help show how individual concepts form a larger whole (Novak & Cañas, 2008). The processes, principles, and methods discovered in the literature had never before been organized systematically into a single coherent framework. Using the concept mapping technique, the codes, or themes were arranged by the authors to form a framework of whole systems design by hand. The focus question guiding the mapping 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 first iteration of codes was also distributed to a group of engineering students (undergraduate and graduate students) enrolled in a sustainable energy class. These students had 20 min 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 (forming a list of twenty codes show in Table 2), which evolved into a broad framework of whole systems design that outlined process, principles, and methods.

After the codes underwent initial revisions, the elements were reexamined under the new codes shown in Table 2. The elements 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

**Table 2 Revised coding list**

| *Code* | *Code - code definition* | *Sources with code* |
|---|---|---|
| PRO1 | PRO1. Establish common goals – Then align incentives. Stakeholders and members of the design team should define shared visions and goals based on economic, ecologic, and social sustainability. Then incentives should be put into place to ensure that the desired outcomes are achieved during the design process. | E1, E2, SD1, A5, A9, A12, M1, E12, E17, A14 |
| PRO2 | PRO2. 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. | SI, A5, E6, S4, A14 |
| PRO3 | PRO3. Share all information with everyone - Communication and information sharing should be direct, open, and effective. Participation should be broad and interdisciplinary, valuing diverse perspectives and including multiple stakeholders throughout all stages of the design process. | E1, S1, E3, SD1, S2, A3, A5, A6, E5, E6, E7, A10, M1, E12, SD4, E13, E17, SD6, S4, A14 |
| DP1 | DP1. Focus on the fundamental desired outcome - Focus on the end-use 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. | E1, SD1, S2, E4, A4, A6, E6, E7, E8, A10, A12, A13, E11, E12, E13, M3, SD6, M5, S3, A14 |
| DP2 | DP2. Learn from nature - Biomimicry, encourages designers to mimic the forms, processes, and systems found in Nature and to consider how their design fits with Nature. | S2, A1, S2, A3, A5, A7, E7, E8, A8, A9, A10, M5, S3, S4, A14 |
| DP3 | DP3. Apply systems thinking - Designers consider the whole system, it's components, and the relationship between them throughout the design process. Designers should 'get the beat of the system," i.e. they should understand system behavior and use baseline values to model the system they are designing. | 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 | DM1.1. Define the scope to align with vision and desired outcomes - Designers should define the scope both temporally and spatially to address the problem and remain true to established visions and goals. | E1, E2, S1, SD1, E6, E8, E9, A12, E12, E13, S4, A14 |
| DM1.2 | DM1.2. Design on a clean sheet - Means to be innovative, creative, and not imitate past designs. Beginning with a clean sheet removes preconceptions and limitations to creativity and innovation in design. | E1, E3, S2, E12, A14 |
| DM1.3 | DM1.3. Start design analysis at the end-use and work upstream - Energy and resources move from supply (us) to end-use (ds), losses of these resources are compounded through each successive step. To turn these compounding losses into compounding benefits by starting savings and benefits downstream and then move upstream. | E1, E2, E3, E13, |

(*continued on next page*)

Table 2 (*continued*)

| *Code* | *Code - code definition* | *Sources with code* |
|---|---|---|
| DM2.1 | DM2.1. Seek simple elegant solutions - Radical simplicity, meaning passive design and simpler systems to achieve the desired outcomes and purpose of the design. This usually results in cost, time, and resource savings. | E1, E4, A4, A11, E14, E16, E18, M4, E19 |
| DM2.2 | DM2.2. 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. | A1, E3, A3, A4, A5, A6, E6, A7, E7, E8, A8, A9, SD3, E9, A12, A13, SD4, M2, SD6, A14 |
| DM2.3 | DM2.3. Move resource impact toward zero - Designing for sustainability requires shifting our resource impacts toward zero. Designers can achieve this my minimizing the demand for resources while maximizing the efficiency of resources used. | 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 | DM2.4. Rethink waste - Radical re-evaluation of waste. Qaste 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 toward zero waste. | A1, E3, E4, A4, E7, A11, E10, M1, A13, E11, E12, SD4, SD5, E13, E15, M2, E16, E17, M3, M4, M5, S3, E19 |
| DM2.5 | DM2.5. Use renewable inputs - Designers should choose inputs for their designs that are from renewable sources when possible. | A1, E4, A4, E5, E7, A9, A10, A11, E10, E11, E13, E15, M2, M3, E19 |
| DM2.6 | DM2.6. Use non-hazardous materials - Whenever possible, inputs for design should be non-hazardous to human, environmental, and economic health. | A1, E3, SD2, E4, A4, SD3, M1, E11, SD4, E13, E14, E16, M3, A14, E19 |
| DM3.1 | DM3.1. 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. | E1, S2, E4, A4, E7, A9, A11, E9, A13, E13, M2, S3 |
| DM3.2 | DM3.2. Protect and restore natural, social, and economic systems - Designs should not harm the natural, social, and economic systems that they are a part of, but rather they should work to heal them. | A1, E3, SD2, A4, A5, E5, E6, A9, A10, SD3, A12, M1, A13, SD4, E13, E15, E19 |
| DM3.3 | DM3.3. 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. | E1, E2, S1, SD1, S2, A4, A5, E6, E7, SD3, A11, A12, M1, M4, SD6, S3, A14, E19 |
| DM3.4 | DM3.4. Consider the entire life-cycle of the system - Designers should design for the entire life-cycle of their solutions and use life-cycle accounting. [Elaborate]. | A1, E3, S2, A3, E4, E5, E6, A8, A10, SD3, E12, E15, E16, E17, M4, M5, S3, A14 |
| DM3.5 | DM3.5. Tunnel through the cost barrier - 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. | E1, E12, A14 |

of coding, some elements from each source were still too specific to their individual applications to be included in the framework.

The second iteration of codes was again arranged into a design framework by hand with concept mapping techniques. To examine alternate perspectives about the relationship between the elements of the framework, the authors conducted one more concept mapping exercise. From the combined efforts of the researchers, a final whole system design framework was formed.

# 2 Results and discussion

The whole systems design framework that emerged from the literature review is organized into three overarching categories: design process, design principles, and design methods. The framework is comprised of 20 total elements and represents the literature in the fields of sustainable development, systems thinking, engineering, architecture, urban design, planning, and sustainable management. Some of the framework's elements such as systems thinking, and tunnel through the cost barrier are broadly applicable across any field of design, while other elements such as renewable inputs, waste mitigation, and hazardous materials more pointedly direct designers to consider sustainability issues. The intent of this framework for whole systems design was to develop consensus amongst the design disciplines and demonstrate that whole systems design is a viable design approach for sustainable solutions. However, each of the framework's elements considered alone does not guarantee that a solution will be sustainable. Along with the elements themselves, a hypothetical urban revitalization project is used as an example to illustrate the elements of the framework.

## 2.1 Design process

The following elements identified throughout the literature describe the *process* of whole systems design. These elements 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.

### 2.1.1 Establish common goals—then align incentives

This process feature 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 Sustainable Development [IISD], 1996; Lovins et al., 2010, p. 7; 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, p. 7). In the case of an urban revitalization project, the design team may establish a goal to reduce the ecological footprint of the site to predevelopment levels and project owners could incentivize this goal by providing financial bonuses for achieving various levels of footprint reduction.

### 2.1.2 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). The design team and project owners should establish a collaborative and open work environment from the beginning to encourage all players to share ideas freely. This means that the architects, engineers, planners, politicians, and residents in the local community all have valuable input and have the opportunity to both listen and be listened to during the design process. One outlet for practicing mutual learning in the case of an urban revitalization project would be the inclusion of a design charrette where all stakeholders bring both concerns and ideas to the project.

### 2.1.3 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 between traditional disciplines, as well as 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, p. 7; McMahon & Hadfield, 2007, p. 247). 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). For an urban revitalization project, designers would again likely utilize a charrette to both share project information with the community and to receive input and feedback for their design. Other means of sharing information openly include: designers interacting with and talking to locals informally about the project at local restaurants, cafes, stores, etc.; designers speaking formally at community meetings; and establishing an interactive project website.

## 2.2 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.

### 2.2.1 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). Architects and engineers involved in revitalizing an urban space would not focus their efforts on implementing a specific green technology or strategy, such as solar panels for rooftops. Instead their intention would be to create a vibrant community that is economically, socially, and environmentally sustainable. In this case, passive solar design options may suit a community better by both increasing energy efficiency and enhancing the esthetic beauty of the area, which encourages people to walk, shop, and enjoy the space.

### 2.2.2 *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, p. 247). Nature minimizes toxicity, celebrates diversity, curbs demand, and makes connections (Benyus, 1998; Macaulay, 2008). Even an interdisciplinary 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). In the case of an urban revitalization project, designers may make use of natural site features such as the natural sloping of the site toward a nearby river to implement curbside bioswales and in turn reduce runoff, improve the water quality, and enhance the connection of the urban and natural environment.

### 2.2.3 *Apply systems thinking*

Systems thinking means that designers consider the whole system, its components, and the relationship between them throughout the design process (Calthorpe et al., 1991; Environmental Protection Agency [EPA] 2010; Lovins et al., 2010, p. 7; 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 some linear thinking with cyclical design (Ehrenfeld, 1997; Holmgren, 2002; Lovins et al., 2010, p. 7; McMahon & Hadfield, 2007, p. 247; 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). Designers can apply the systems thinking principle to an urban infill and revitalization project by using sophisticated predevelopment metrics to establish a baseline predevelopment environmental impact assessment of habitat, water, and energy to assess their progress on achieving previously defined ecological footprint goals.

## 2.3 Design methods

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

### 2.3.1 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 within established visions and goals (Anastas & Zimmerman, 2003; Lovins et al., 2010, p. 7; 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 should also consider ecologic, social, and economic factors that align with the goals and visions of the project when defining the scope. Designers for the urban revitalization project could examine the project as a series of phases and time horizons such as a 5-year, 10-year, or even a 50-year revitalization plan for the neighborhood. Also when selecting which part of the city to begin the revitalization and infill process, designers would carefully select a location that would catalyze additional projects and development.

### 2.3.2 Design on a clean sheet

A phrase coined by the Rocky Mountain Institute, "designing on a clean sheet" means to avoid simply imitating past designs (Lovins et al., 2010, p. 7). 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 assumptions, testing and exploring every possibility, and allowing ideas to evolve and shape over time (Macaulay, 2008). Applying this method, the design team for the urban revitalization project would begin their design efforts without immediately looking at previous master plans or designs for the targeted neighborhood. Removing preconceptions from the design table early in the process creates an environment more conducive to creativity and innovation. Looking at previous designs for the area would be appropriate once the design team has an opportunity to put all their ideas out on the table.

### 2.3.3 Start design analysis at the end-use and work upstream

As energy and resources move from supply (upstream) to end-use (downstream), losses of these resources are compounded through each successive step. The Rocky Mountain Institute suggests that designers turn these compounding losses into compounding benefits by starting savings and benefits first downstream and then move upstream (Boyle & Coates, 2005; EPA, 2010; Lovins et al., 2010, p. 7; "TNEP Engineering Sustainable Solutions Program," 2011). In the case of the urban revitalization project, designers would look at the end-use of energy, water, and resources for the neighborhood to accelerate their goal of a predevelopment ecological footprint. This would mean looking to building retrofits for resource efficiency to compound their resource savings further upstream at the power and water treatment plants.

### 2.3.4 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, p.30; Lovins et al., 2010, p. 7; Mendler et al., 2006; Thompson, 1999; Tsoulfas & Pappis, 2006). This usually results in cost, time, and resource savings and reduces waste. For example, applying this method to the urban revitalization project could entail using deciduous trees to shade buildings and people in the hot summer months and allow sunlight through during the colder winter.

### 2.3.5 Value place

A method commonly practiced by urban designers, planners, and architects, valuing place means understanding, respecting, and integrating the local culture, geography, values, and history into the design (EPA, 2010; Lovins et al., 1994; McDonough, 1992). The best solutions often 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 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). For the urban renewal project, the design team could interview residents and local businesses, and immerse themselves in the neighborhood to gain insight about the history, culture, and values of the place. From this field research, the design team can reflect the local values in the design to preserve the local architectural heritage and create a meaningful interface between the built environment and the community.

### 2.3.6 Move resource impact toward zero

Designing for sustainability requires shifting our resource impacts toward zero. Designers can achieve this by minimizing the demand for resources while maximizing the efficiency of resources that are used (Anastas, 2000, p.30; Gagnon et al., 2009; Lovins et al., 2010, p. 7; Lovins et al., 1999, p. 16; Luttropp & Lagerstedt, 2006; The Earth Charter, 2000). The principle implies increasing the efficiency of a design throughout its life cycle, including the usage phase. Also, renewable resources should be consumed at rates below the regeneration rate (Ceres Principles, 1989; Cote et al., 2006; Daly, 1991; Shu-Yang et al., 2004). The urban renewal design team could enhance neighborhood walkability and integrate mass transit to reduce auto-dependency, in turn minimizing the demand for fossil fuels.

### 2.3.7 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 toward zero waste (Benyus, 1998; Holmgren, 2002; Lovins et al., 1999, p. 16; 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). In an effort to move toward a predevelopment ecological footprint, the urban design team could implement a rainwater recovery system in the neighborhood so that stormwater runoff is no longer treated as a waste, instead becoming "food" for nonpotable uses.

### 2.3.8 Use renewable inputs

Designers should consider inputs for their designs that are from renewable sources. 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). In the case of an urban revitalization project, integrating solar, wind, or geothermal energy into the urban grid could be an effective way for the design team to generate energy without using fossil fuels, which are nonrenewable at the rate we use them.

### 2.3.9 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). An application of this principle in the urban renewal scenario may mean specifying and using materials and processes that are non-hazardous for building retrofits and infrastructure improvements.

### 2.3.10 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, p. 7; Sweeney, n.d). Integrating the elements of a design leads to synergistic solutions that can reduce costs and negative impacts associated with a project. A design team looking to revitalize an urban neighborhood and achieve significant sustainability goals could consider using low-impact development (LID) techniques to manage stormwater, a big concern in urban environments where impervious surfaces run rampant.

LID techniques such as bioswales and rain gardens achieve multiple benefits. For example, they manage stormwater, treat runoff on site, and enhance aesthetics by integrating thoughtful green space into the urban fabric.

### 2.3.11 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, 2010; Ljungberg, 2007; McDonough, 1992; Shu-Yang et al., 2004; Todd, 1994). An early-established goal in an urban renewal project can address this principle: by designing the urban fabric to have a predevelopment ecologic footprint, the design team is protecting natural, social, and economic systems.

### 2.3.12 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, p. 7; Meadows, 2008; TNEP Engineering Sustainable Solutions Program, 2011). In an urban renewal project, feedback loops can come in many forms and at many strategically defined places. A design team could require performance measurements for various phases of the redevelopment to ensure the designed system is operating at targeted levels.

### 2.3.13 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, 2010; McDonough, 1992; McMahon & Hadfield, 2007, p. 247; 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). Designers tackling an urban revitalization project could consider and plan for timely retrofits of existing building stock, as well as design future structures that can adapt to changing uses over time.

### 2.3.14 Tunnel through the cost barrier

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, p. 7; Lovins et al., 1999, p. 16; Macaulay, 2008). Back to the urban renewal example, the design team could implement a neighborhood wide retrofit strategy of the existing building stock that suggested superinsulation and energy efficient windows as a means to downsize air conditioning systems, save money, and reduce energy demands.

## 2.4 The framework for sustainable whole systems design

These processes, principles, and methods distilled from 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 elements are visually organized into a framework outlining the process, principles, and methods of whole systems design shown in Figure 2. Related processes, principles, and methods are arranged under the same columns and are also indicated by shading.

For example, consider the first column in Figure 2, the process in that column is "establish a common vision – then align goals and incentives." Chronologically, this makes sense as the first element of the framework. The first principle beneath this 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 methods and steps implemented by designers at the beginning of design analysis.

Similar logic was used to group the processes, principles, and methods in columns two and three. In column two, the common threads were related to a learner's mindset, and in particular learning from nature. The design

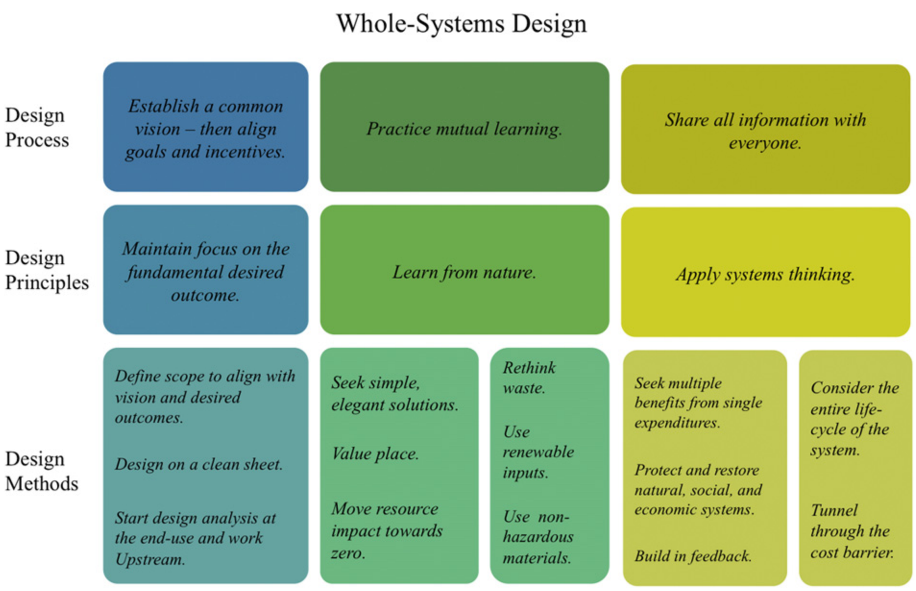


*Figure 2 Whole systems Design framework*

methods present in the second column are all common to biomimicry and biomimetic design thinking, which is defined as looking to nature for design advice. The third column is linked together by a holistic, systems approach. In a holistic approach, all stakeholders are included throughout the process, which is how the process "share all information with everyone" links to systems thinking. The design methods in column 3, including: multiple benefits from single expenditures, feedback, protecting systems, life-cycle analysis, and the thinking required to "tunnel through the cost barrier" all require systems thinking. 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 (top row), was a design principle to be considered (middle row), or was a method that could be applied by designers (bottom row). The organization of this framework is not set in stone. Future testing of the framework and expert input will help refine the organization of the framework even further.

# 3 Conclusions

Meeting local and global challenges like energy, water, food, poverty, educational gaps, and environmental degradation will require a drastic change in the way we design our world. These issues are intertwined, and whole systems design is an approach that offers designers the opportunity to holistically optimize solutions for social, environmental, and economic sustainability. However, whole systems design has remained largely undefined and its elements ambiguous, making it a difficult design paradigm to implement. This research addresses this issue by expanding the boundaries of the literature to synthesize processes, principles, and methods into a framework for sustainable whole systems design.

Frameworks can communicate and encourage widespread application of principles that may otherwise be difficult to understand. A food pyramid is a framework that helps us see what a healthy diet looks like. Six Sigma and the Plan-Do-Check–Act cycle are frameworks that help organizations implement quality enhancement programs. Sustainable building rating systems, such as LEED in the U.S. and BREEAM in the U.K., are also frameworks. They help practitioners translate the idea of a sustainable building into specific steps and actions. The rigorously developed framework for sustainable whole systems design can be a starting point to a similar tool for the design process. Like the food pyramid, this framework for whole systems design is meant to make abstract ideas more tangible. We hope the framework can help enable more effective education in this area and more widespread application of whole systems design in practice, both of which will lead to more sustainable designs.

The next step to build on the research described here is to test and validate the framework for sustainable whole systems design. Several related areas of future research are possible with the development of this framework. These include:

- Further validating the design framework: Seeking expert input on the principles, processes, and methods of whole systems design outlined in this framework and mapping the framework to real world design scenarios and outcomes.
- Measuring characteristics of whole systems designers: For example, systems thinking and the ability to see the interrelatedness of individual parts is essential to 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.
- Establishing and testing methods for teaching the framework: A variety of pedagogies should be investigated. Particularly promising are interactive and problem-based approaches that allow students to work with the elements of whole systems design rather than simply memorize them.
- Developing design tools to aid designers through the complex process: Tools to help designers collaborate, think non-linearly, and challenge their past mental models are key to expanded use and success of the whole systems design process.

## Acknowledgements

This material is based upon work supported by the National Science Foundation Graduate Research Fellowship under Grant No. NSF DGE 0751278.

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