

The Science and Engineering of Sustainability: A Primer

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Defining Sustainability

The concept of sustainability is gaining increased interest as a potential solution for the myriad of global, regional, and local problems facing society in the late twentieth century. Even as developing nations struggle with issues of overpopulation, disease, and political conflict, developed countries such as the United States must balance problems such as infrastructure deterioration, pollution, and urban sprawl with limited economic and physical resources to solve them. Sustainability offers a new way of looking at problems on both large and small scales, seeking to ensure that the needs of humanity are met in the present without endangering the potential for future human needs to be met.

Sustainability reconciles the ubiquitous human drive to improve our quality of life with the limitations imposed on us by our global context. It requires unique solutions for improving our welfare that do not come at the cost of degrading the environment or impinging on the well-being of other people. Although there is no general agreement regarding the precise meaning of sustainability beyond respect for the quality of life for future generations, most interpretations and definitions of the term "sustainable" refer to the viability of natural resources and ecosystems over time, and to the maintenance of human living standards and economic development (National Science and Technology Council 1994).

Sustainability is a relationship, or balancing act, between many factors (social, environmental and economic realities and constraints) that are constantly changing (Munasinghe & McNeely 1995; Vanegas et al. 1995; Pirages 1994). The concept of sustainability was first accorded widespread public recognition as a result of the 1992 Earth Summit in Rio de Janeiro, within the context of sustainable development. The United Nations World Commission on Environment and Development coined a definition of sustainable development in their report presented at the Summit which is probably the most well-known in all of the sustainability literature: "development that meets the needs of the present without compromising the ability of future generations to meet their own needs." (WCED 1987, p. 43).

In order to determine a sound and useful understanding of sustainability with respect to engineering and science, we must examine more closely the fundamental ideas underlying the concept at a global level. One example of a strategy for sustainability which takes a prescriptive form is the Natural Step, developed by Karl-Henrik Rob rt of Sweden. The Natural Step consists of four prescriptive statements, developed using a unique consensus process which included some of the finest scientific minds in Europe. The four statements which make up the Natural Step are shown in Table 1. These steps provide guidance for selecting alternatives to solve particular problems being addressed. Rob rt goes farther than most authorities in stating how to achieve sustainability: he

recommends starting with the “lowest hanging fruits” on the tree of sustainability problems, to achieve a step-by-step progress toward sustainability, one “natural step” at a time (Holmberg & Rob ert 1997).

Natural Step System Conditions
1) Substances from the Earth’s crust must not systematically increase in nature.
2) Substances produced by society must not systematically increase in nature.
3) The physical basis for the productivity and diversity of nature must not be systematically deteriorated.
4) Basic human needs must be met with the most resource-efficient methods possible, including a just resource distribution.

Table 1: Natural Step System Conditions (Rob ert & Eriksson 1994)

In another popular framework or model of sustainability developed by Munasinghe (1993), sustainability issues are classified into three categories: social/political, environmental, and economic issues. These three classes of issues are arranged in the model as vertices of a triangle (Figure 1), whose equilateral sides are intended to imply that achieving sustainability involves finding solutions which balance the importance and impacts of each of the three categories.

Munasinghe’s triangle provides a good classification system for sustainability properties, and highlights issues such as social and political impacts which have often been omitted from consideration in traditional design processes, or otherwise overshadowed by variables such as time, cost, and quality.

Herman Daly, academic economist and author of many works on theoretical sustainability, provides another example of the state of the art in attempting to operationalize sustainability for decision making. Daly has developed a set of what he calls “operational principles for sustainable development”, which provide a set of rules or principles for implementing sustainability in the context of development projects. Daly’s operational principles are shown in Table 2, serving as a framework that identifies critical variables in achieving sustainability, as well as proposing specific operational limits to those variables to define what is and is not sustainable.

Daly’s operational principles are a relatively unique work in the theoretical sustainability literature. While most authorities on theoretical sustainability tend to focus on specific disagreements about particular limits or strategies for achieving sustainability, Daly simply cuts through the layers of argument and selects limits for each relevant variable which seem reasonable based on the arguments he presents.

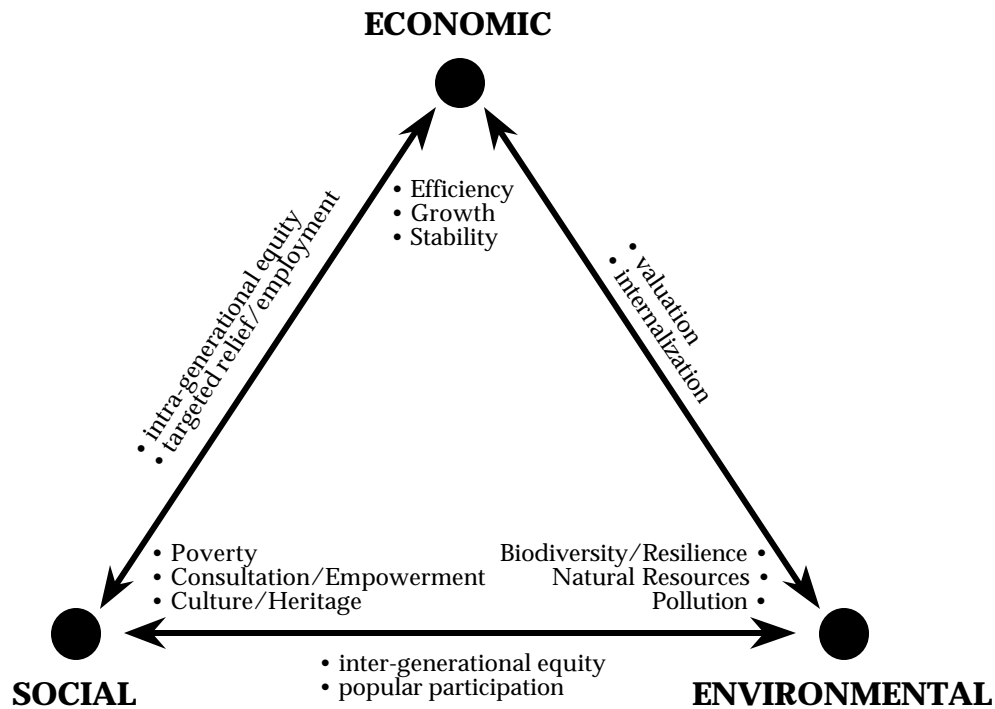


Figure B.2: Approaches to Sustainable Development
(from Munasinghe 1993)

Sustainability Issue	Operational Principle
1a) Resource Consumption - Renewable	“[H]arvest rates should equal regeneration rates (sustained yield)”
1b) Resource Consumption - Nonrenewable	“[Limit] their rate of depletion to the rate of creation of renewable substitutes”
2) Ecosystem Impacts	“[W]aste emission rates should equal the natural assimilative capacities of the ecosystems into which the wastes are emitted”
3) Economics/Social	“[T]he scale of the economy (population times per capita resource use) must be within the carrying capacity of the region in the sense that the human scale can be maintained without resorting to capital consumption. Ultimately this will imply a limit on total scale of resource throughput, which in turn implies limits on and a tradeoff between population size and per capital resource use in the region”

Table 2: Operational Principles of Sustainable Development (after Daly 1990)

Because sustainability is a dynamic concept rather than a static state, it requires decision makers to be flexible and willing to modify their approaches according to changes in the environment, human needs and desires, or technological advances. This means that actions that contribute to sustainability today, either in perception or in reality, may be deemed detrimental tomorrow if the *context* has changed:

Ensuring sustainability over time means maintaining a dynamic balance among a growing human population and its demands, the changing capabilities of the physical environment to absorb the wastes of human activity, the changing possibilities opened up by new knowledge and technological changes and the values, aspirations and institutions that channel human behaviour. Thus, visions of a sustainable world must naturally change in response to shifts in any part of this dynamic relationship (Pirages 1994, p. 200).

For the engineer and designer, creating sustainable systems involves making engineering and design decisions based on multiple dimensions: technology, ecology, economics, and socio-cultural, including ethics (Carpenter 1995), and using available tools and applications to implement these decisions. W.R. Moomaw presents a sustainability triangle which includes culture, economy, and environment as the three vertices, with human well-being enclosed in the middle (Moomaw 1996). S.R. Carpenter (1995) has adapted this triangle for the context of engineering design by enclosing technology in the middle (Figure 2). That is, we are concerned with the interactions and impacts of technology on all dimensions of sustainability.

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Figure 2: The Dimensions of Sustainability for Engineering Design (Carpenter 1995)

Achieving sustainability means designing our actions and making our decisions within the boundaries of the triangle. Individuals choose how to balance their decisions, but in order to do so we must have some understanding of the elements of these dimensions—what they mean, how to evaluate and calculate tradeoffs, and how to consider these tradeoffs when making decisions. The following sections of this chapter consider each of the four dimensions (Technological, Ecological/Environmental, Economic, and Social/Ethical Sustainability) in turn, and present definitions, debates and major themes, and examples of considerations for each dimension.

The dimensions of sustainability are not independent of one another, but instead intertwine in the tradeoffs that are inherent in any engineering decision. These interrelationships among dimensions create the complexity inherent in sustainable engineering design and decision making. The next sections describe the basic scientific foundations upon which the concept of sustainability is built.

Thermodynamic Foundations

In order for any system to be perfectly sustainable, there must be no net loss of the sum total of matter and energy circulating within the system. Such a state is possible for the system defined as Earth – energy lost as thermal radiation from the earth can be offset by solar radiation absorbed from the sun.

In addition to conservation of matter and energy, the state of entropy within the system must be stable in order for the system to survive into perpetuity (Georgescu-Roegen 1971). Entropy is the degree of disorder of a system, and is usually the inverse of the potential usefulness something has for humans. For example, an unlit match has lower entropy and higher potential usefulness than a match which has already been lit and extinguished. By lighting the match, we as humans can make use of its potential energy; however, as the match is lit and extinguished, its entropy increases irreversibly - you cannot unlight a match!

In all systems, entropy increases with every expenditure of energy, and can only be offset in one system by a greater sacrifice of entropy in some other system; therefore, the net entropy of the universe is continually increasing toward a state of disorder (Van Wylen & Sonntag 1985). Fortunately for the human species, the potential exists for the amount of energy received by earth from the sun to exceed the amount of energy lost as thermal radiation (the difference is commonly called the solar energy budget), and can be used to offset increases in entropy resulting from transformations of matter and energy within the earth system. Thus sustainability is theoretically possible for the system defined as Earth. Perfect sustainability for the earth system is theoretically possible as long as the inhabitants of Earth consume less energy than supplied by the solar energy budget and as long as the sun continues to shine. To remain within this budget (described quantitatively by Vitousek et al. 1986), two global objectives of sustainability can be identified:

- 1) **Ecosystem Impact:** Minimize negative impacts on natural ecosystems (since they are the mechanism for capturing solar energy in the form of photosynthesis)
- 2) **Resource Consumption:** Minimize the gain in entropy as a result of consumption-related processes.

These basic physical constraints represent limits within which actions on Earth must remain in order to be sustainable. However, they must be considered in the context of anthropocentric or human concerns in order to provide a useful concept for engineering and technology, whose basic goal is to meet human needs and aspirations.

The Human Component

In describing how humans are affected by actions to increase sustainability, it is necessary to consider the issues of inter-generational (between generations) and intra-generational (within generations) equity (WCED 1987), as well as the self-interest of those whose task is to achieve sustainability. To elaborate, three basic objectives can be identified:

- **Motivation for Initiators:** Maintain standards of living at least as high as the ones that currently exist
- **Intergenerational Equity:** Leave the earth in at least as good a condition as it presently exists
- **Intragenerational Equity:** Bring everyone else up to at least a “decent” standard of living.

The first of these goals, maintain standards of living at least as high as the ones which currently exist, is borne of practical considerations. By definition, no rationally self-interested person will voluntarily sacrifice his or her own standard of living without some compensating benefit of equal or greater utility (Simon 1983). Moreover, reliance on such constructs as conscience or guilt to motivate human behavior to become more sustainable is unwise, since such motives tend to be generally unreliable and often self-extinguishing (Hardin 1968). Therefore, in order to foster acceptance of any proposal for sustainability, assurances must be included that those who undertake to change their lifestyles to achieve sustainability will benefit as a result of their commitment.

The second goal, leave the earth in at least as good a condition as it presently exists, is aimed at achieving intergenerational equity. By leaving the earth as good as or better than at present, decision-makers ensure that future generations will not only have the same set of resources with which to work, but also the accumulated body of lessons learned that humans have developed as a result of our life experiences. The phrase “at least as good” has been interpreted in various ways in the sustainability literature, ranging from leaving the nonrenewable resource base completely unchanged from its present state (as discussed in Daly 1994), to using nonrenewable resources as necessary provided that adequate substitutes are created (e.g., Solow 1993; Mikesell 1992). Adopting the more conservative view described by Daly, the ultimate goal should be to strive to leave resource bases and natural ecosystems as unchanged or improved as possible while working toward achieving the first and third goals.

The third goal, bring everyone else up to at least a “decent” standard of living, is concerned with the issue of intragenerational equity. In defining what comprises a “decent” standard of living, this investigation stipulates the interpretation of Liverman et al. with respect to setting a threshold of acceptability: survival of the human species “with a quality of life beyond mere biological survival” (1988, p. 133). To what level beyond mere biological survival is a question that is largely culturally dependent. In situations where the biological survival of human individuals is currently infeasible, taking action to improve living conditions to the point of survival is a first step toward intragenerational equity. In other situations such as in developed countries, living standards are generally far above the minimum required for basic human survival, and fall under the first constraint discussed earlier: Motivation for Initiators.

Achieving intragenerational equity is important not only because of ethical considerations for the welfare of people in developing nations, but also because humans cannot hope to develop common goals and a coordinated course of action for achieving sustainability when people are concerned for their very survival and lacking in basic human rights (e.g.,

Jacob 1994). Common goals and coordinated action are required to achieve sustainability because no action within the earth system is entirely without ramifications for other entities and processes in the system. Due to the contextual nature of sustainability, actions which seem rational and sustainable to one party acting in isolation may actively conflict with the rational actions of other parties in the interconnected “real world” (DuBose 1994; Hodge 1995; Cernea 1993). Thus, global objectives and cooperative actions are needed to reach a state of sustainability, and achieving some degree of intragenerational equity is essential to elicit that cooperation (Ruckelshaus 1989; Mink 1993).

The next step is to consider how these thermodynamic and human objectives translate into three objectives of sustainability at a technology level, and show what must be considered to evaluate the sustainability of a technological system in general.

What Makes Technologies Sustainable?

Technology plays a very important role in sustainable development because it is one of the most significant ways in which we interact with our environment; we use technologies to extract natural resources, to modify them for human purposes, and to adapt our man-made living space (Vanegas et al. 1995). It is through use of technology to create engineered systems that we have seen drastic improvements in the quality of life of many people. Unfortunately, many of these short term improvements in the immediate quality of life have also exacted a great toll on the environment. In order to proceed toward sustainability, we will have to be more deliberate and thoughtful in our employment of technology. We need to develop and use technologies with sustainability in mind. We need “sustainable technologies.”

A sustainable technology is one that promotes a societal move toward sustainability, a technology that fits well with the goals of sustainable development. Sustainable technologies are practical solutions to achieve economic development and human satisfaction in harmony with the environment. These technologies serve to contribute, support or advance sustainable development by reducing risk, enhancing cost effectiveness, improving process efficiency, and creating processes, products or services that are environmentally beneficial or benign, while benefiting humans (National Science and Technology Council 1994, p. 4). To qualify as sustainable technologies, these solutions must have the following characteristics, in addition to meeting traditional engineering requirements and constraints (Vanegas et al. 1995; Vanegas & Pearce 1997):

- *Minimize use of nonrenewable energy and natural resources*
- *Satisfying human needs and aspirations with sensitivity to cultural context*
- *Minimal negative impact on the earth's ecosystems*

Minimizing Consumption of Matter and Energy. The use of nonrenewable energy and natural resources should be minimized because consumption of resources inherently involves increasing the disorder of materials and energy, rendering them of lower utility for future use (Roberts 1994; Rees 1990). By subjecting materials and energy to consumption processes we decrease their potential utility to current and future

generations. Therefore, consuming as little matter and energy as possible, or “doing more with less,” is a fundamental objective of sustainability.

Meeting Human Needs and Aspirations. A sustainable technology must fulfill the needs of the population it is intended to serve. In fulfilling those needs the technology must account for human preferences and cultural differences. In some cases these preferences may conflict with environmental and economic criteria and a compromise will have to be worked out. This does not mean that human preferences should be ignored; fulfillment of our desires means the difference between surviving and living.

Minimizing Negative Environmental Impacts. Finally, causing minimal negative environmental impacts (as well as maximizing positive impacts) is an important objective of sustainability since the environment consists of ecosystems whose ongoing health is essential for human survival on earth (Goodland 1994). Sustainability of the human race requires that ecosystems be protected and preserved in a reasonable state of health through maintaining biodiversity, adequate habitat, and ecosystem resilience (Norton 1992).

How Can We Make Technologies More Sustainable?

In order to understand the changes that need to be made to develop sustainable technologies, it is useful to look at the paradigm which is currently being employed. Despite a wide range of positions and opinions on the subject of sustainability, there is general agreement that the current paradigm of linear development, which disregards constraints to material or energy consumption, is unsustainable. In Figure 3, a model of the unsustainable linear development approach is shown which has prevailed over the last few centuries. In this model, several systems are linked in a linear process that begins with both renewable and non-renewable natural resources such as air, water, soil, mineral or biological resources. In this model, *exploitation and use of primary natural resources* occurs to provide inputs for industrial processes (Subsystem 1). The outputs of this system become the principal inputs for two other systems: the *production and use of energy* (Subsystem 2), whose output is a critical input to all the systems in the linear process; and *resource processing and manufacturing* (Subsystem 3), whose output is a set of industry-specific products or services that are *transported and commercialized* within Subsystem 4.

The linear process ends with the *use and consumption* (Subsystem 5) of the products or services generated by the industrial system across all segments of society. This process has two additional outputs from each of its systems, which are at the core of many problems facing the world today: increasing amounts of hazardous and non-hazardous waste, and increasing levels of environmental impact.

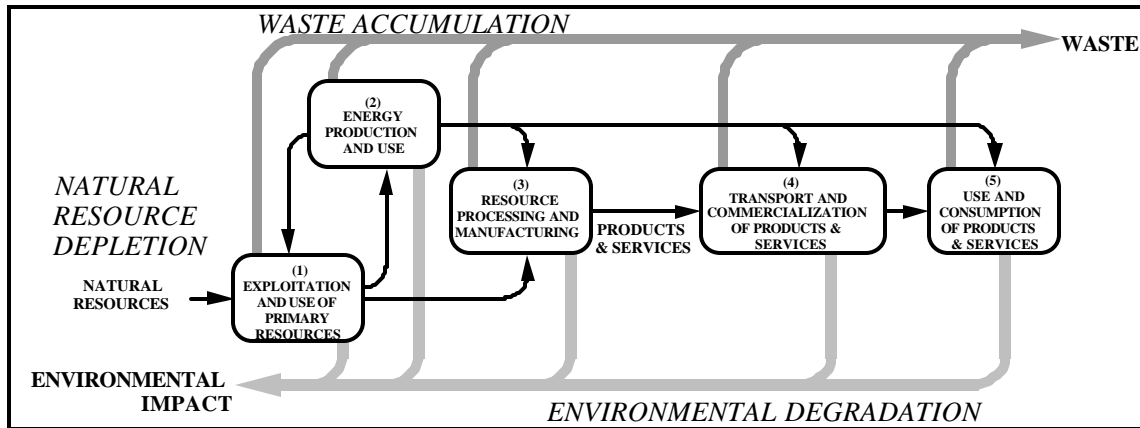


Figure 3: Unsustainable Linear Development
(Vanegas et al. 1995; adapted from Roberts 1994)

The process is linear because inputs enter at Subsystem 1 and move in one direction through the system to Subsystem 5 and then are disposed, going through the system only once with no cycling of materials. To aggravate the situation even more, this linear process is fueled by continuous increases in the demand for, use, and consumption of products and services, creating pressures for further exploitation of natural resources, and for continued expansion of energy production, resource processing, and manufacturing capabilities. This unrelenting growth has created three serious problems: natural resource depletion, accumulation of waste, and environmental degradation. It is these challenges which must be addressed in achieving sustainability.

A new way of thinking must be adopted to redirect our development toward sustainability. This cyclic sustainable process is a direct response to the challenges and problems posed by the unsustainable linear process described above in Figure 3, and offers a mechanism to gradually overcome the problems of unsustainability.

The framework for a sustainable system presented in Figure 4 highlights one way of looking at this new approach. Developed from original ideas by D. V. Roberts, this system shows how to implement two of the three criteria for sustainable technology: frugal in use of nonrenewable energy and natural resources; and minimal negative impact on the earth's ecosystems. The criteria regarding the satisfaction of human needs and aspirations is not represented explicitly in this figure but nonetheless remains important.

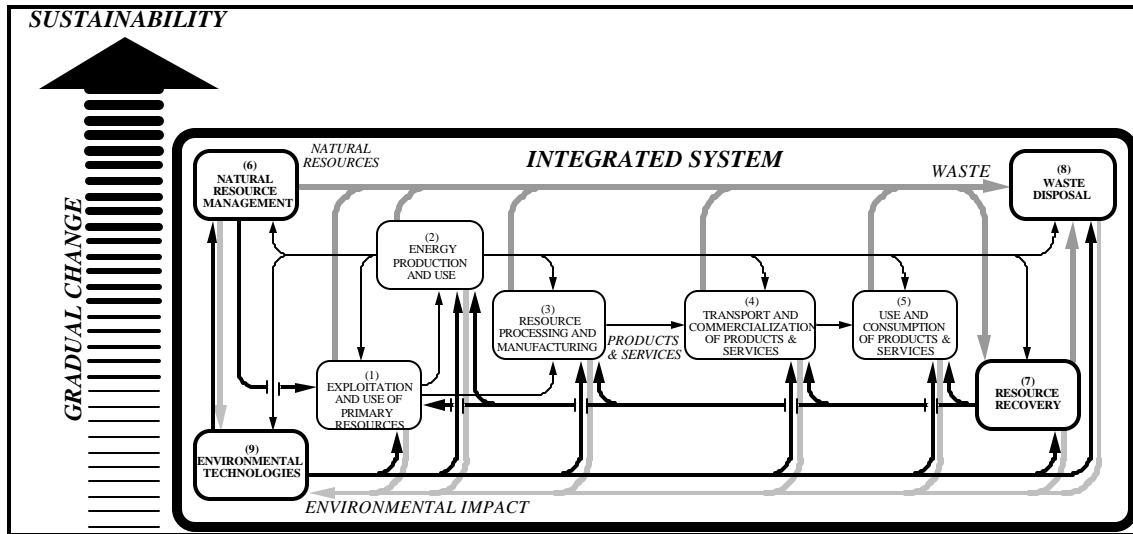


Figure 4: Cyclic Sustainable Development Process
(Vanegas et al. 1995; adapted from Roberts 1994)

First, instead of a linear process, the framework represents a closed cyclical system. The total integrated system includes the same five systems described earlier as a part of the linear system, and in addition, it incorporates four new subsystems, each a response to a specific sustainability challenge:

- *Natural resource management (Subsystem 6)* addresses the need to manage the exploitation of renewable natural resources in a way that ensures that the supply will always exceed the demand. At the same time, this management system monitors and controls the use of non-renewable natural resources to prevent their total depletion.
- *Resource recovery (Subsystem 7)* addresses the need to recover and recycle selected resources and products from waste. These recovered resources would then become inputs to the five basic subsystems in the linear framework. They also would contribute to reducing the amount of waste that requires disposal.
- *Waste disposal (Subsystem 8)* recognizes that a certain amount of waste is inevitable, and thus will require disposal in ways that are not detrimental to the environment.
- *Environmental technologies (Subsystem 9)* addresses the need to incorporate proactively, in every subsystem within the framework, strategies and mechanisms that mitigate environmental impacts at the root – before the impact happens, through the application of preservation, pollution prevention, avoidance, monitoring, assessment and control strategies and mechanisms. This subsystem also takes into account that some damage already has been done to the environment, and that corrective actions such as remediation or restoration are necessary.

Sustainable technologies should adopt this cyclic closed loop system, which mimics natural systems. In this system the generation of waste is avoided; instead, all by-products are used as inputs back into production or as inputs into some other process. By minimizing waste environmental impact is lessened. Because the scale of impact is kept low in this system, change to the environment will be gradual and the surrounding environment will be able to adapt and remain healthy.

The role of the engineer in making engineering systems more sustainable is to integrate science and technology, experience, and innovation in developing practical applications to solve problems (Figure 5).

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Figure 5: Role of the Engineer in Achieving Sustainable Development
(D.V. Roberts 1994)

Roberts proposes that in order to make engineering systems more sustainable, we as engineers must shift from a linear approach to meeting human needs (Figure 3) to a cyclical approach, which treats the global context in which we all exist as an essentially closed system (Figure 4). Toward this end, Roberts identifies seven areas of opportunity for engineers to have an impact on increasing the sustainability of engineered systems:

- 1) Managing and developing natural resources
- 2) Processing and modifying resources to meet human needs
- 3) Improving existing transportation systems
- 4) Improving consumption patterns
- 5) Recovering and reusing resources
- 6) Restoring the natural environment
- 7) Improving energy production and use practices.

Finding engineering solutions to these challenges must be a priority if engineering systems are to be made more sustainable.

In addition to working collectively as a profession to achieve sustainability, engineers as individuals have additional responsibilities to ensure that the goal is met of making engineering systems more sustainable. Roberts proposes four categories of actions which engineers can undertake on an individual basis to work toward this goal:

- 1) Become informed about environmental issues
- 2) Inform others about sustainability
- 3) Do a better job of environmental planning on projects
- 4) Become environmental leaders and decision makers.

Besides these environment-centered directives proposed by Roberts, an additional component of ethical responsibility is described by Thom (1994):

It is beyond question that use of technology has had an enormous impact on what is called 'life support'. Let me mention ozone, climate change, acid rain, and biodiversity. Doctors swear an oath with respect to their responsibility for life. How different now is the position of the technologies? We must confront and decide this question, because our future is bound up in the answer.

Making engineering systems more sustainable involves not only paying more attention to the impacts our actions have on the natural world in which we exist, but also attending to the needs of our own species – humanity. In addition to these new criteria for engineering and design, we also must not lose sight of the two criteria which have served as the primary guidelines for engineering activities in the past: technological performance and economics. Thus, designing sustainable engineering systems involves making decisions based on four categories of attributes: technology, ecology, economics and ethics (after Carpenter 1995).

Suggested References - For Starters

- [Cernea 1993] Cernea, M.M. (1993). "The Sociologist's Approach to Sustainable Development," *Finance & Development*, December, 11-13.
- [Costanza et al. 1995] Costanza, R., Meadows, D., and Hawken, P. (1995). "Envisioning a Sustainable and Desirable United States." Unpublished preliminary proposal, International Society for Ecological Economics, Solomons, MD.
- [Daly 1990] Daly, H.E. (1990). "Towards Some Operational Principles of Sustainable Development," *Ecological Economics*, 2(1), 1-6.
- [Daly 1993] Daly, H.E. (1993). "From Empty-world Economics to Full-world Economics: Recognizing an Historical Turning Point in Economic Development," in Goodland, Robert, et al., eds., *Population, Technology, and Lifestyle - The Transition to Sustainability*. Island Press, Washington, DC, pp. 23-37.
- [Daly & Cobb 1994] Daly, H.E., and Cobb, J.B., Jr. (1994). *For the Common Good*, 2nd ed. Beacon Press, Boston, MA.
- [DuBose 1994] DuBose, J.R. (1994). "Sustainability as an Inherently Contextual Concept: Some Lessons from Agricultural Development." M.S. Thesis, School of Public Policy, Georgia Institute of Technology, Atlanta, GA.

- [Georgescu-Roegen 1971] Georgescu-Roegen, N. (1971). "The Entropy Law and the Economic Problem," *University of Alabama Distinguished Lecture Series*, n. 1.
- [Goodland 1994] Goodland, R. (1992). "The Case that the World has Reached Limits," in Goodland, Robert, et al., eds., *Population, Technology, and Lifestyle - The Transition to Sustainability*. Island Press, Washington, DC, pp. 3-22.
- [Greene 1994] Greene, D.L. (1994). "Transportation and Energy," *Transportation Quarterly*, v. 48, n. 1, pp. 91-101.
- [Hardin 1968] Hardin, G. (1968). "The Tragedy of the Commons," *Science*, v. 162, pp. 1243-48.
- [Hawken 1994] Hawken, P. (1994). *The Ecology of Commerce*. Harper-Collins Publishers, New York.
- [Hodge 1995] Hodge, R.A. (1995). "Assessing Progress Toward Sustainability: Development of a Systemic Framework and Reporting Structure." Ph.D. (interdisciplinary) Dissertation, School of Urban Planning, Faculty of Engineering, McGill University, Montreal, Quebec, Canada.
- [Jacob 1994] Jacob, M. (1994). "Toward a Methodological Critique of Sustainable Development," *J. Developing Areas*, v. 28, pp. 237-252, January.
- [Mikesell 1992] Mikesell, R.F. (1992). "Project Evaluation and Resource Sustainability," *Contemporary Policy Issues*, v. 10, pp. 83-88, October.
- [Mink 1993] Mink, S. (1993). "Poverty and the Environment," *Finance & Development*, December, 8-9.
- [Munasinghe & McNeely 1995] Munasinghe, M. and McNeely, J. (1995). "Key Concepts and Terminology of Sustainable Development." in Munasinghe, M. and Shearer, W., eds. *Defining and Measuring Sustainability: The Biogeophysical Foundations*. World Bank, Washington, DC.
- [Norton 1994] Norton, B.G. (1994). "Sustainability: Two Competing Paradigms." Working paper prepared for a February 18th conference at Texas A&M University.
- [Rees 1990] Rees, W.E. (1990). "The Ecology of Sustainable Development," *The Ecologist*, v. 20, n. 1, pp. 18-23.

- [Rifkin 1980] Rifkin, J., with Howard, T. (1980). *Entropy - A New World View*. Viking Press, New York.
- [Robért et al. 1994] Robért, K.H., Holmberg, J., and Eriksson, K.E. (1994). "Socio-ecological Principles for a Sustainable Society - Scientific Background and Swedish Experience." Revised excerpt for book on ISEE Meeting, Costa Rica.
- [Roberts 1994] Roberts, D.V. (1994). "Sustainable Development – A Challenge for the Engineering Profession," in Ellis, M.D., ed. *The Role of Engineering in Sustainable Development*. American Association of Engineering Societies, Washington, DC. pp. 44-61.
- [Ruckleshaus 1989] Ruckleshaus, W.D. (1989). "Toward a Sustainable World," *Scientific American*, v. , pp. 166-175, September.
- [Simon 1983] Simon, H.A. (1983). "Alternative visions of rationality," in *Reason in human affairs*, pp. 7-35, Stanford University Press, Stanford, CA.
- [Solow 1991] Solow, R.M. (1991). "Sustainability: An Economist's Perspective." Eighteenth J. Seward Johnson Lecture to the Marine Policy Center, Woods Hole Oceanographic Institution, Woods Hole, MA. June 14.
- [Thom 1994] Thom, D. (1994). "Engineering to Sustain the Environment," in Ellis, M.D., ed. *The Role of Engineering in Sustainable Development*. American Association of Engineering Societies, Washington, DC. pp. 62-80.
- [Vitousek et al. 1986] Vitousek, P.M., Ehrlich, P.R., Ehrlich, A.H., and Matson, P.A. (1986). "Human Appropriation of the Products of Photosynthesis," *BioScience*, v. 36, n. 6, pp. 368-373.
- [WCED 1987] WCED - World Commission on Environment and Development. (1987). *Our Common Future*. Oxford University Press, Oxford, UK.