Metrics and Methodology for Sustainable Development[1]

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Abstract

As a concept, sustainable development (SD) emerged in response to the combined effect of population growth, technology, and affluence or poverty, depending upon the location. Where affluence causes unsustainable development, such as in developed nations, the drivers of greater sustainability are the “externalities” of development (e.g., the accelerating depletion of natural resources and wildlife). This driver combines with the ever-present need for economically-defensible solutions and with the pressure of global inequity of distribution of the benefits of development to form the three-legged rationale for SD. This rationale is the foundation for creating a new framework for development. The framework of sustainability is already under construction. Two fundamental influences fuel its construction: (1) changes in values that re-define policies and funding priorities and (2) improved scientific data and understanding of complex, integrated physical and biological earth systems and natural limits.

Although manifest in different ways, both the public and private sectors are beginning to see how unsustainable practices may produce undesirable effects on their organizations, customers, communities, and the future at large. Professionals in fields as diverse as manufacturing, architecture, and federal policy are discovering and instituting ways to apply sustainability concepts, modify existing products or practices, and add new ones. As changes progress from policy through planning to engineering, the client – whether public or private – will demand sustainability expertise from the consultant. The consultant who understands the value of sustainable development early on and can demonstrate a credible methodology for applying SD to hard engineering will emerge with a distinct advantage.

Currently two approaches to applying SD are prevalent: adopt “green” features and apply a specified methodology, such as one using metrics and targets. The first approach, while both popular and faster, is sometimes reminiscent of blindly shooting darts and proclaiming achievement. Lasting credibility and genuinely effective application of SD principles demand more rigorous processes.

One of the first traits to emerge in the SD discipline was the use of indicators, or metrics, that measure sustainability. The terms indicators and metrics are used interchangeably in this paper. Metrics form the core of a methodological process for

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assessing sustainability and incorporating it into an outcome, such as a new product or infrastructure. Quantifying the metrics and setting performance targets strengthens their use. Clearly tying metrics to baseline conditions, such as state and driving force indicators, links intended outcomes to current conditions. The metrics should be readily applied as project or product criteria. The targets quantitatively indicate which alternative solutions are superior to meet the intended performance. Expanding the involvement of stakeholders at critical points in the process and producing a well-documented process supports the defensibility of the client's decisions.

Introduction

Sustainable development is an emerging mechanism for considering the impacts of population growth, economic and technical development, and resource depletion. While embraced by several government agencies and progressive businesses, the practical application of sustainable development is only just now entering the field of consulting engineering. This paper introduces a methodology for conducting a rigorous sustainably analysis suited to engineering projects and decision making processes. The methodology includes defined steps and the use of indicators or metrics.[2]

The Scientific Basis for Sustainable Development

Sustainable development is largely viewed as building on the four systems principles introduced in 1989 by Karl-Henrik Robert, a Swedish oncologist, in concert with 50 scientists and supported by economists, business leaders, and others. The premise is that there are system limits to the natural world and that we must ultimately comply with these limits if we are to provide – or preserve – thriving human life with dignity and pleasure. The first three system conditions are based on the first and second laws of thermodynamics[i] and the fourth is social in nature. The four system conditions state that for a society to be sustainable, nature's functions and diversity are not systematically:

1. Subject to increasing concentrations of substances extracted from the earth's crust;
2. Subject to increasing concentrations of substances produced by society, or
3. Impoverished by overharvesting or other forms of ecosystem manipulation.
4. Resources are used fairly and efficiently in order to meet basic human needs worldwide.

A summary of the rationale behind the four system conditions is shown in Table 1.

Table 1

[2] The terms indicators and metrics are used interchangeably in this paper.

Rationale for the Four System Conditions

Condition Topic	System Condition	Meaning	Rationale	Example
Substances mined or extracted from nature	Substances from the earth's crust must systematically increase in the ecosphere	Fossil fuels, metals, and other minerals must not be extracted at a faster rate than their slow re-deposit and re-integration into the earth's crust.	If this condition is not met, the concentrations or substances in the ecosphere will increase and eventually reach limits – often unknown – beyond which irreversible changes occur. Nothing disappears and everything disperses	Tar and oil from petroleum, mercury lead arsenic uranium
Synthetic compounds, other manmade materials	Substances produced by society must not systematically increase in the ecosphere	Substances must not be produced at a faster rate than that at which they can be broken down and integrated into cycles of nature or redeposited into the earth's crust.	If this condition is not met, the concentration of substances in the ecosphere will increase and eventually reach limits – often unknown – beyond which irreversible changes occur. Nothing disappears and everything disperse.	Formaldehyde, dioxin, polychlorinated biphenyls (PCBs), synthetic fibers. Endocrine disrupters
Ecosystem manipulation	The physical basis for productivity and diversity of nature must not be systematically diminished.	We cannot harvest or manipulate ecosystems in such as way that productive capacity, ecosystem services, and biodiversity systematically diminish.	Our health and prosperity depend on the capacity of nature to reconcentrate and restructure wastes into new resources. Human activities need to work in harmony with the cyclic principle of nature.	Urban sprawl, exotic species invasion, elimination of predators, ocean warming, over fishing, pesticide spread, excessive water diversion
Socio-economics	There must be fair and efficient use of resources with respect to meeting human needs.	Basic human needs must be met with the most resource efficient methods possible.	Unless basin human needs are met worldwide through fair and efficient use of resources, it will be difficult to meet conditions 1-3 on a global scale.	Deforestation to meet energy needs, wildlife poaching to meet economic needs, political upheaval that eliminates environmental protection

Modified from Nattrass and Altomare, 1999.[ii]

Techniques and Tools for Getting Started

The four system conditions provide a solid basis for a sustainability analysis and goal setting. Yet the conditions are so broad and overarching that they are not readily applied at the project scale. The following sections of this paper offer useful guidelines and tools for integrating SD into projects. The guidelines and tools apply information on the past and present (forecasting) and apply future scenarios (backcasting). The initial phase of a project should contain the following two elements:

- a clear set of guiding principles developed with the stakeholders and endorsed by them
- a sufficiently broad set of baseline conditions to clearly link metrics and targets

to existing conditions and later showing how future outcomes will directly improve the level of sustainability.

Guiding Principles

Guiding principles are qualitative statements that, for SD, embody whole-systems thinking. Whole-systems thinking looks at the project as a whole – how decisions, systems, and designs are interrelated, and how one influences the other.[iii]

To use the four systems conditions to develop guiding principles, the system conditions will need to be broken down into sufficient detail or to a small enough scale to be meaningful. For example, in a land development project near of Los Angeles, the guiding principles were defined for each element of the project that was either critical for the development or impacted by the development. Guiding principles were prepared for siting, biological resources, construction materials, solid waste, energy, water, transportation, human communities, and building mechanical systems. Initially, broad statements were developed that reflected the desired direction, acting like a compass to move the project toward sustainability. The principles captured the sustainable development concepts in a non-quantified fashion. Each of the following guiding principles represents one of a handful of guiding principles developed for each element in that project.

Biological Resources – In areas where natural communities will be modified, enhance and maintain ecosystem features using "best management practices" for chaparral ecosystems (e.g., using native species on the golf course).

Water – Water systems will allow for substantially less water consumption than in traditional, comparable developments (e.g., onsite reuse for toilet flushing and landscape irrigation of low-water use plants).

Energy – Significantly reduce energy consumption with respect to comparable development facilities, using green building design, facility management, demand reduction, efficient building systems, and other methods.[iv]

Human Communities – Design the project to promote a sense of place and a sense of ownership of the community. Provide opportunities for frequent, casual interaction of residents, visitors, and employees (e.g., for a hotel renovation).

Stakeholder involvement is very important when developing guiding principles. Stakeholders include the owner, the owner's staff, and generally includes others such as regulatory agencies, representatives of local community and environmental groups, neighbors, and the lender. Frequently, this task is performed without the engineer's participation as a stakeholder. This should be discouraged since the ability to embed sustainability into technical solutions relies heavily on the engineer's capacity to understand and apply SD within the project constraints. Thus, the engineer is a stakeholder during the planning and design stages of the project.

Baseline Conditions

Baseline conditions help form the basis of decision making. The more accurate and complete the baseline information, the greater the potential for sound decision making. Frequently, engineers are not able to work with a complete set of technical baseline conditions relevant to a particular project. Even less frequently, engineers seek non-technical information to define the broader set of baseline conditions. Typically, engineering baseline conditions focus on the site, operating capacity, age of equipment and structures, efficiency, maintenance, or other technical aspects. Baseline conditions might include characteristics of the general population such as growth and consumption patterns. Extensive definition of the social influences and affected biological resources rarely occurs until much later during an environmental impacts assessment. The engineer has little information with which to evaluate the sustainability of technical solutions and lacks sustainability criteria on which to build solutions. Guiding principles defined at the outset will focus the collection of non-technical baseline conditions. Since the baseline conditions may be foreign to the engineer, the use of planners or other disciplines to assist in this step may improve the work product.

Guiding principles can be used to help identify baseline state and driving force indicators. State Indicators are measures of the quality of the environment, society, or economy. An environmental state indicator measures the quality of the environment and the quantity of natural resources, and includes the health effects caused by the deterioration of the environment on human populations and ecosystems.[v] Driving force or pressure indicators measure the pressure on the environment caused by human activities. Performance or response indicators measure the efforts undertaken by society to respond to environmental changes and issues. Pressure, state, and performance indicators should be clearly linked in the project as shown in Table 2.

Table 2

Examples of Linked Pressure, State, and Performance Indicators

Pressure Indicator	State Indicator	Performance Indicator
Rate of ground water withdrawal	Depth to ground water	Rate of ground water recharge using reclaimed water
Area consumed annually by urban expansion	Population of red-tailed hawks	**Amount** of land preserved for hawk habitat
Harvesting rate of Alaskan king crab	Distribution of crab population	Moratorium on crab fishing until population re-establishes itself

Note that failing to adequately identify baseline conditions may lead to environmental surprises. These may come in the form of a discontinuity, a synergism, or an unnoticed trend. A discontinuity is an abrupt shift in a trend or previously stable state. A synergism is a change in which several phenomena combine to produce a more powerful effect as witnessed along the Yangtze river:

> "The monstrous 1998 flood of China's Yangtze River did $30 billion in damages, displaced 223 million people, and killed another 3,700. The damage was a synergism caused not just by heavy rains, but by extremely dense settlement of the floodplain and by deforestation – the Yangtze basin has lost 85 percent of its forest cover."[vi]

Forecasting

Since the objective of sustainability is to address those elements that have frequently been considered externalities to a project, these externalities can now be brought into the project by following the guiding principles and quantitatively defining baseline conditions. Forecasting of both externalities and internalities, as shown in Figures 1 and 2, effectively defines baseline conditions from current trends.

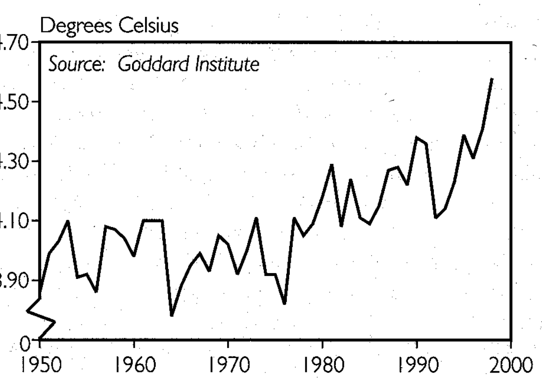

Figure 1. Average Temperature at Earth's Surface, 1950-1998

Source of both figures: Worldwatch Institute 2000

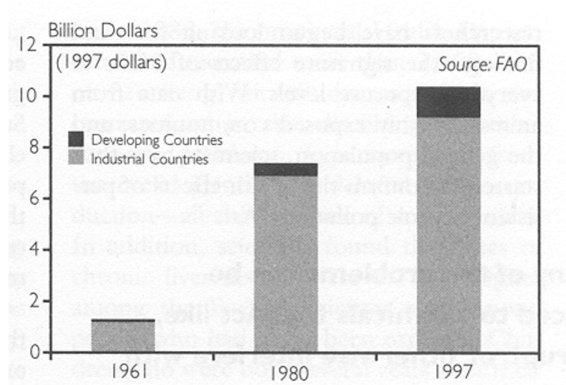

Figure 2. Pesticides Exported from the Top 30 Countries, Selected Years

Defining and Using Metrics

Many examples of sustainability indicators exist. The most widely-published sets of indicators were developed by governmental agencies for large scale tracking of progress, typically on at a national scale (e.g., United Nations) or municipal scale (e.g., Seattle).

Manufacturers are also developing indicators, such as through the World Business Council for Sustainable Development (WBCSD). These indicators tend to focus on eco-efficiency. Eco-efficiency is defined by WBCSD[vii] as the delivery of competitively-priced goods and services that satisfy human needs and bring quality of life, while progressively reducing ecological impacts and resource intensity throughout the life-cycle to a level at least in line with the Earth's estimated carrying capacity. Several of the member corporations of WBCSD apply "generically applicable indicators" (indicators common to most businesses) and "business specific indicators" (indicators that are considered unique to a specific company). Examples of these indicators are available in the environmental sections of the corporate annual reports of its members. Note a valuable lesson in sustainability is the recognition of the social context of corporations. These corporations have elected to allow greater transparency of operations through the publishing of this information. This may be in recognition that a public response to corporate and government actions, particularly with regard to environmental impacts and human rights, is a manifestation of natural limits, i.e. sustainability. Indeed, the Monsanto Company states its hope that the published eco-efficiency indicators system will provide a transparent and useful way for stakeholders to understand and evaluate the eco-efficiency of Monsanto.[viii] Monsanto's indicators fall into categories of (1) Product and Service Value, which consists of information about the quantity of goods and services produced or provided to customers, earnings before interest and taxes and net sales; and (2) Environmental Influence Indicators which consists of information about items such as energy consumed, materials consumed, greenhouse gases emitted and others.

Frequently, neither public agency indicators nor the manufacturers' indicators are of much use for projects such as infrastructure. Metrics must be defined relative to the specific project. If the baseline conditions are well defined and guiding principles in place through a workshop or other forum for stakeholder involvement, developing metrics should be a relatively straightforward task.

The Border Environment Cooperation Commission (BECC) is a bi-national federal agency formed by a side agreement of NAFTA. The BECC is charged with promoting the development of environmental infrastructure within the border region on both sides of the United States-Mexico border. The BECC adopted a process for assessing the sustainability of planned infrastructure projects. The process includes stakeholder workshops to identify indicators applicable and relevant to the communities that are seeking infrastructure improvements. In the majority of the projects, the BECC hires consulting engineers to perform the work. The work tasks include conventional engineering services integrated with sustainable development. The engineering firm is expected to adequately define baseline conditions, conduct workshops with stakeholders, and prepare a draft set of project indicators. The draft indicators are refined during a workshop. [ix]

In the BECC process, once indicators are defined they easily become project criteria, whether for an infrastructure master plan, water main replacement, transfer station design, or treatment plant expansion. The BECC provides examples of indicators that are applicable to these types of projects, although not all of the indicators are quantified.

When developing metrics, keep in mind that the metrics should be clearly linked to baseline conditions and represent key areas needing improvement. Society tends to respond to what gets measured -- so measure what's important. For the project, develop as many indicators as are practicable as design or project criteria. And check that the indicators relate back to the four system conditions.

Indicators may be developed from the three fundamental aspects of sustainability as shown in Table 3. By breaking down these categories into greater and greater detail, it is possible to derive quantitative indicators suited to a specific project. The American Society of Civil Engineers developed criteria for sustainability of water resources.[x] Some of these criteria included in Table 3 show how water-related indicators can be derived from more general criteria.

The relative importance of each indicator may vary. When indicators are used as design criteria, stakeholders should agree on the relative weights. A workshop with the stakeholders to assign weights will help the engineer to focus on the most important performance aspects of the alternatives.

Setting Targets

While metrics are useful because they are measurable and they force one to focus on what is important, they do not suggest a target level of sustainability, but simply a unit of measure. Metrics by themselves do not create a road map to sustainable development. Setting a performance scale and specific target value for sustainability for each metric will greatly strengthen the achievability and the likelihood of genuinely improving sustainability. For example, in the land development project near Los Angeles, an assigned metric was the reduction of water consumed for landscaping. By reviewing what other forward-thinking developers had achieved in similar climates, it was possible to set a realistic performance scale and a target value of 50% reduction over typical landscaping water consumption. Furthermore, by using this scale when evaluating technical options, it became apparent if the target was set at the right level. Interestingly, assigning optimistic target values raises the expectation and likelihood of achieving a higher level of sustainability.

Backcasting

Setting sustainability targets may be derived from comparing performance on similar projects or by backcasting. Backcasting is a planning method used to attain new goals and define truly new conditions. Backcasting is about framing goals within the context of a desired future state, and determining short-term decisions and financial commitments needed to achieve that goal. Long-term goals may be defined by the guiding principles, but short-term steps – even very small steps -- will be taken to reach that goal. Those steps that are easiest to take and will achieve results that help the move the client closer to its goals should be part of a step-by step implementation strategy. For back-casting to be effective, stakeholders must be willing to proactively understand the larger environmental and social context, and strategically assess the

Table 3

Criteria and Examples of Indicators for Environmental, Economic, and Social Sustainability[xi]

Social Sustainability

Sub-element	Criteria	Sub-Criteria Elements	Examples of Quantitative Indicators
Institutional development	Flexibility and sustainability of infrastructure work Management opportunities for multifunctional use Opportunities to adapt to changing circumstances Improved technical and organizational efficiency	Opportunities for a phased development Opportunities for multifunctional use and management to respond to changing conditions Sustainable quality of structures (corrosion, wear) Opportunities for rehabilitation of the original situation (autonomous regeneration, active reconstruction and restoration).	Ratio of staff hired to staff required to maintain infrastructure Number of institutional barriers to promote new ways to get more water use from less water through cooperative responsibility sharing among water, wastewater, and public health agencies Level of environmental management system with monitoring, record keeping, and feedback loops
Public health	Promote public health, safety, and well-being	Effects on public health Effects on safety (risks) Effects on annoyance/hindrance (smell, dust, noise, crowding) Effects on living and working conditions	Number of reported incidences of water-borne disease Number of regulatory violations Presence of risk management and emergency response plans that meet the standard of practice Measured level of nuisance (noise, odor, traffic, etc.)

Social Sustainability

Sub-element	Criteria	Sub-Criteria Elements	Examples of Quantitative Indicators
Socio-cultural aspects	Empower diverse stakeholders	Share authority for determining infrastructure development and use, including use for economic gain	Extent of institutional and legal instruments allowing onsite reuse of wastewater (e.g., for economic gain)
	Promote public participation	Stakeholder involvement in planning and decision making	Number of stakeholders represented and participating in decision making process
		Public outreach and information	
	Safeguard societal virtues	Public trust	Number of avenues to provide transparency in decision making processes and operations
	Promote social mobility and cohesion	Upward-mobility opportunities for disadvantaged groups	Number of students participating in agency-sponsored youth programs to promote social mobility (e.g., high school programs to expose disadvantaged youth to careers in operations, engineering, and public administration)
		Social resiliency and stability	
	Strengthen cultural identity	Effects on cultural heritage	Extent to which policies or actions support preservation of traditional livelihoods, activities, and land use patterns
		Avoid sprawl-inducing growth	

Social Sustainability			
Sub-element	Criteria	Sub-Criteria Elements	Examples of Quantitative Indicators
Equity	Equitable distribution of benefits and responsibilities	Effects on income distribution Effects on educational opportunities Equitable distribution of resource Equitable distribution of services	Number of water supply shutoffs Effectiveness of rate structure to accommodate public health needs of poverty-stricken users. Number of sewer backups per neighborhood
Economic Sustainability			
Economic Development	Local and larger-scale economies	Effective use of resources and infrastructure for local economic prosperity Ability to foster stable, diverse, and resilient economic base. Impact of local resource use on others' economies	Number of businesses that the agency helped to use onsite or offsite recycled water Amount of water flow available to down stream communities
Cost Efficiency	Cost efficient distribution and use of resources	Cost efficient distribution of resources Cost efficient use of resources Effect of cost burden on local economy	Ratio of cost for the level of treatment to number of gallons used *that actually require that level of treatment* Gradient of rate structure to promote water conservation Ratio of average cost of service to median household income

Environmental Sustainability			
Sub-element	Criteria	Sub-Criteria Elements	Examples of Quantitative Indicators
Ecosystem integrity and biodiversity	The use of natural and environmental resources (including raw materials) and discharge of wastes must fall within the carrying capacity of natural systems Enhance and conserve natural and environmental resources, and even improve the carrying capacity of natural and environmental resources	Raw materials and energy Waste discharges (closing materials cycles) Use of natural resources (water) Effects on resilience and vulnerability of nature Water conservation Accretion of land or coast Improvement and conservation of soil fertility Nature development and conservation of natural values	Flow quantity and variability versus required flows to maintain the ecosystem carrying capacity of the source water Number of measures to lower energy use instituted in equipment selection, construction practices, operations, and by contractors. Number of sensors used to reduce energy consumed by non-essential uses
Global environmental issues	Avoid negative effect on global resources	Air quality impacts, particularly greenhouse gases Effect on fisheries Materials consumed by operations and administration	Quantity of carbon dioxide emitted from WWTP operations Number of fish species and their populations in receiving water Tons of polymer and paper purchased and volume of solid waste disposed per year

project's current reality within this whole-system perspective. Using the four system conditions, strategic visioning through back-casting from a desirable future will help identify targets and strategic steps to move the project from its current reality to the desired sustainability goals.

Developing and Evaluating Alternatives

Developing the Alternatives

When developing technical solutions, SD criteria help to define appropriate technology and management practices. Objectivity is critical when developing and assessing technical solutions using new criteria that lead the engineer to think outside of the box. Satisfying the environmental and social criteria prior to the economic criteria provides more opportunity for discovering new solutions. An iterative process may be necessary to balance the three-sided competing needs of sustainability.

Life cycle cost analysis is essential. Because sustainable development focuses on a long planning horizon (50 to 100 years), clearly identify life cycle costs for each alternative.

Evaluating the Alternatives

The final steps covered in this paper are for evaluating the alternatives. Using the scale for each indicator, the desired target performance, and the relative weighting of indicators, the relative sustainability of the technical solutions becomes apparent. Figure 3 is an example of a scale prepared for evaluating wastewater treatment alternatives.[xii] The criterion, removal of heavy metals, was selected through a public process. The scale was prepared and the performance of the alternatives evaluated by the engineer. Each criterion was treated in this manner.

Rating of Alternatives for Heavy Metals

Alt 2	Alt 3	Alt 4	Alt 5	Alt 6	Evaluation Scale
		♦	♦		5. Excellent dilution capacity. Excellent settling capacity. Good precipitation potential. Good bio-adsorption potential.
♦	♦			♦	4. Good dilution capacity. Good settling capacity. Good precipitation potential. Good bio-adsorption potential.
					3. Good dilution capacity. Good settling capacity. Limited precipitation potential. Limited bio-adsorption potential.
					2. Good dilution capacity. Good settling capacity. No precipitation potential. No bio-adsorption potential.
					1. Limited dilution capacity. Limited settling capacity. No precipitation potential. No bio-adsorption potential.

Figure 3. Scale for Evaluating Treatment Alternatives for Heavy Metal Removal.
Source: CH2M HILL 1997

A final workshop with stakeholders helps the stakeholders arrive at a decision. The final outcome will be a result of the criteria, technical analysis, and the public process. The criterion shown in Figure 3 was aggregated with other parameters to produce one criterion for water quality. This criterion was used with other criteria in a public workshop to produce a transparent basis for decision as shown in Figure 4.

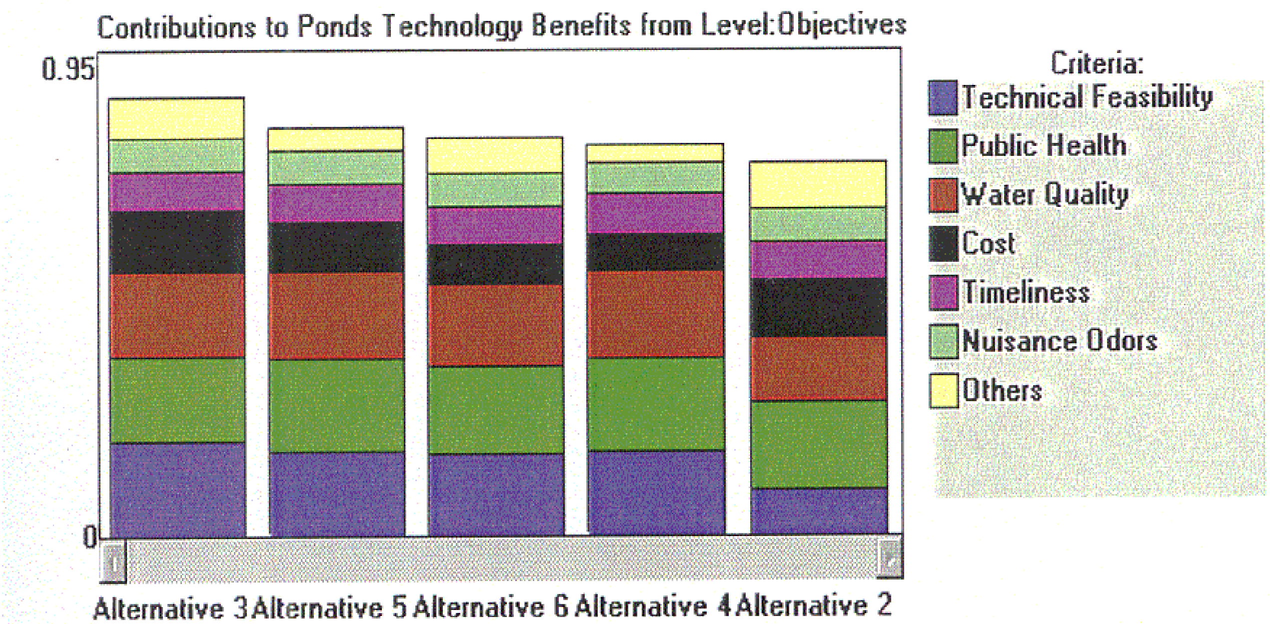

Figure 4. Contribution of weighted criteria and scaled performance of alternatives to the selection of the preferred alternative.

Source: CH2M HILL 1997.

Three benefits result from the series of workshops: transparency of decision making, the public exposure to rigorous engineering science, and endorsement of the final outcome. This approach may avoid long or costly delays from regulators or special interests.

Final Notes

The process described herein is a rigorous approach to applying sustainable development to engineering projects. There may be situations where the full process is infeasible, but portions of it may be applied within the constraints of the project. To be effective, SD must be integral to the project with a sustainability analysis conducted early. Following development of alternatives, take care to ensure that design specifications and further engineering, construction and implementation activities continue to fulfill the established criteria. The engineering field still needs specifications and best management practices that embody sustainable development. The ability to perform a credible sustainability analysis and provide effective specs and BMPs will act as a differentiator for the consulting engineers who develop them early.

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