Perspective

Sustainable Development and Sustainability Metrics

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Introduction

If Rachel Carson's *Silent Spring*, published in 1962, can be credited for the public realization of widespread environmental degradation directly or indirectly attributable to industrial enterprise, the book *Our Common Future* (WCED, 1987), which is the report of the World Commission on Environment and Development, must be considered the most important catalyst for the worldwide appreciation for the idea of sustainable development. Qualitatively, the concept of sustainable development is simple enough: the natural resources of the Earth are limited; they are being used disproportionately by a minority of people living in the wealthy nations, thus creating *intra*-generational inequity. The rate of use of these resources is ever-increasing, thus depriving the future generations of a living standard comparable to that of the present, and creating *inter*-generational inequity.

The underlying philosophy of sustainable development is that the natural resources belong to all humans whose aspiration to higher standards of living should not be rendered limited. The point of view, according to the WCED report, is that the present wasteful lifestyle of the developed nations is not sustainable on account of their disproportionately large per capita resource consumption that results in environmental degradation and societal inequity. In fact, some scholars have estimated that supporting the present standard of living seen in the developed nations for all mankind with the current technologies requires the natural resources of two additional Earths (Wackernagel and Rees, 1996). The rallying wisdom behind sustainable development, therefore, is for restraining the rate of use of material and nonrenewable energy now so as to keep enough for many future generations to fulfill their own ambitions of living standards. Hawken et al. (1999) asserted that this could be achieved with technologies that are four times as resource-efficient as the current ones. This is the so-called Factor 4 idea, in contrast to the previous assertion of the Factor 10 idea that advocated the need for improving the efficiencies by an order of magnitude. Thus, sustainable development is thought to be a wise balance among economic development, environmental stewardship, and societal equity. In some business circles this is referred to as the triple bottom line.

One could at this point ask: could these ideas be quantified somehow and, if so, how can chemical engineers help in the realization of sustainable development?

Clearly, the goal of achieving sustainability is socio-political and cannot be achieved by technology alone. Yet, it is by creating economic value through the development of environmentally preferable technologies that chemical engineers can participate in the process of sustainable development. Chemical engineering as a discipline is inherently integrative, i.e., it uses the systems approach to process design. Chemical engineers are traditionally known for designing and operating process plants that manage specific chemistries with constraints of material utilization, cost, and safety. For over a decade now, chemical engineers have been incorporating environment concerns into process design and operation. The early stages of this practice focused on waste treatment—the so-called end-of-pipe approach—and, more recently, the effort was directed to preventing waste by the design of cleaner processes. Sustainability brings out the additional dimension of societal good and equity. The system-based thinking, analysis, and integration, that has been progressively advanced from process to plant network to supply chain management to include environmental concerns, is a powerful methodology that could be used for incorporating societal considerations as well. To begin to approach process or product design from this perspective requires some new tools, i.e., metrics for measuring progress towards sustainability. The societal aspects of sustainability may appear as a particularly difficult problem for inclusion within quantitative metrics, but in the technology parlance, in the opinion of this author, it should be thought of as nothing more than socially responsible technologies, i.e., technologies that provide quantifiable benefits for all.

New challenges to process design have been discussed in this column several times in the recent past. The use of a life cycle assessment technique to design environmentally conscious processes has been discussed by Allen and Shonnard (2001). More recently, Bakshi and Fiksel (2003) provided a perspective on how ecological concerns can be incorporated in design methodology for manufacturing systems. The considerations presented here deal mainly with a framework that would be useful in incorporating sustainability ideas through the use of appropriate quantitative metrics.

What is Sustainability Anyway?

This is undoubtedly a difficult question to answer. A consensus "straw man" definition that a group of professionals from various scientific, engineering, economic, and ecology backgrounds at the U.S. EPA's National Risk Management Research Laboratory suggested is that "sustainability occurs when we maintain or improve the material and social conditions for human health and the environment over time without exceeding the ecological capabilities that support them." According to Clift (2000), sustainability can be thought of as the goal, sustainable development, as the process for achieving it. However, is it actually possible or just an article of faith that we can keep maintaining human health and ecological conditions at a well defined state without exceeding the ecological capabilities in the face of increasing population and the associated demand and need for growth?

If we accept the belief that the Earth's nonrenewable resources decline with uncontrolled economic development, we are forced to conclude that the best we can do is to considerably slow down this decline to meet the challenges posed by population growth and inevitable development. This is clearly possible since the advancement of science and technologies has given us steadily increasing energy and material efficiencies in producing goods and services (Batterham, 2003). However, at the same time, we must be cognizant of potential adverse impacts of otherwise favorable events, such as the environmental impact of the green revolution (Evenson and Gollin, 2003), and plan to avert such impacts by proper planning, for instance, by using genetically modified seeds. The definition of sustainability given above, nevertheless, leaves room for expanding the ecological resource base. The Earth is an open system from an energy perspective: the ultimate source of energy, i.e., the Sun, is for all practical purposes unlimited within our lifetime and that of generations to come. By better harnessing solar energy, we can, in principle, realize increased vegetation and lower life forms that working up through the food chain would provide sustenance for humans. This inference can be derived from the attempts that have been made in valuing the nature's ecological services (Daily, 1997; Costanza et al., 1997). To augment this presumed outcome, economic development has to be based on, in addition, a continually declining use of inorganic resources, which are limited. To attain the sustainability goal thus delineated, however, the underlying development must be economically sound and globally realizable. The practicality of this premise, although not foreseeable in the near future, will always depend on socio-political realities. The practice of science has little control over those realities.

The WCED treatise on sustainability centers on global conditions of ecology (i.e., environment), economic development (i.e., by technologies), and societal equity. The envisioned system in this thinking is the Earth. The idea since has been extended to include constituent systems. Thus, we hear about sustainability of communities, cities, businesses, and even of technologies. We can identify four types of sustainable systems (Sikdar, 2003):

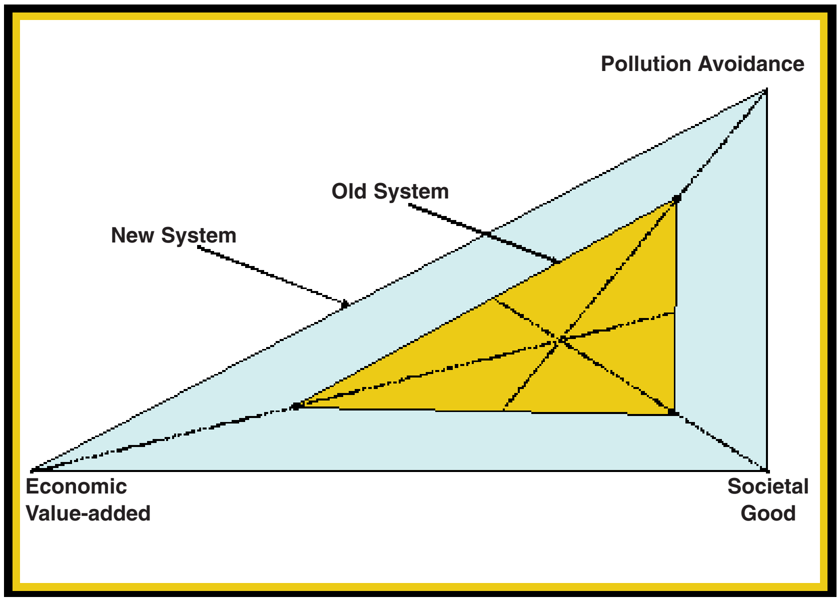

Figure 1. Progress towards sustainability by balancing the three aspects of sustainability.

Type I: Type I systems typify global concerns or problems, such as global warming due to the emissions of carbon dioxide, methane, nitrogen oxides, etc., ozone depletion due to chlorofluorocarbons, or the use of genetically modified (GM) crops. A system of this type is defined as the Earth in relation to one of these global issues resulting from anthropogenic practices. Because of the global nature of these issues, it is not surprising that global treaties and agreements are needed to address them. The Kyoto Protocol for greenhouse gases and Montreal agreement on the phasing out of chlorofluorocarbons are examples of such treaties. Removing scientific uncertainties from environmental, developmental, and social impacts resulting from these global causes is the primary role of the science experts so as to enable the political leaders to craft robust agreements for the benefit of human health and the environment.

Type II: Type II systems are characterized by geographical boundaries. Examples are cities, villages, or defined ecosystems. Technical disciplines that must be marshaled to consider these systems are: civil engineering, environmental engineering, hydrology, ecology, urban planning, law, and economics.

Type III: Businesses, either localized or distributed, constitute Type III systems. Businesses strive to be sustainable by practicing cleaner technologies, recycling byproducts, eliminating waste products, reducing emissions of greenhouse gases, eliminating the use of toxic substances, and reducing energy intensity of processes. For instance, by co-locating manufacturing plants so as to minimize wastes (so-called industrial ecology), or by establishing waste exchange, industries can achieve the three-fold goal of economic development, environmental stewardship, and social good.

Type IV: Type IV systems are the smallest of the systems and they can be called "sustainable technologies". Any particular technology that is designed to provide economic value through clean chemistries would be an example of a Type IV system. Clearly, Type III and Type IV systems are most suitable for an important role for chemical engineers because the performance of these systems is dependent on process and product designs and manufacturing methods.

For all practical purposes, we cannot guarantee the sustainability of any system we choose for consideration. We can, however, make comparative assertion about the state of a system to be more sustainable than another. For a purely illustrative purpose, if we could fashion aggregate metrics for pollution avoidance, economic value-added and societal good, we could show this comparison in the triangular diagram as in Figure 1, in which each vertex represents one of these metrics. In an earlier work the classification of the sustainable systems and potential metrics for decision-making was discussed (Sikdar, 2003). This work reviews the salient features of the systems and metrics classification and provides a suggestion that a hierarchical approach can be used for the metrics for design and analysis of Type III and Type IV systems for making assertions about progress towards sustainability.

In Figure 1 the old system is depicted by the smaller triangle with appropriate values of the aggregate metrics. Only by improving all three aspects of sustainability simultaneously can we claim to have moved the system towards sustainability. It should be clear that the outer triangle could have an infinite number of possibilities based on the practical measures taken to make the improvements. The improvement in any one aspect can be small or large, thus determining the shape of the triangle.

It would be useful if it were possible to construct Figure 1 from industrial performance data. We are still not at a point to be able to integrate constituent data into aggregate metrics required for Figure 1. It is necessary, therefore, to consider the data that we can collect and the metrics we can use in order to capture the three aspects of sustainability.

For any system belonging to any of the four types referred to above, three intersecting circles can illustrate sustainability, as shown in Figure 2 (Azapagic and Perdan, 2000). Each circle in this depiction represents one of the three "legs" of sustainability, i.e., economic aspects, ecological (or environmental) aspects, and societal aspects. Figure 2 is helpful in defining the types of metrics necessary to characterize progress towards sustainability.

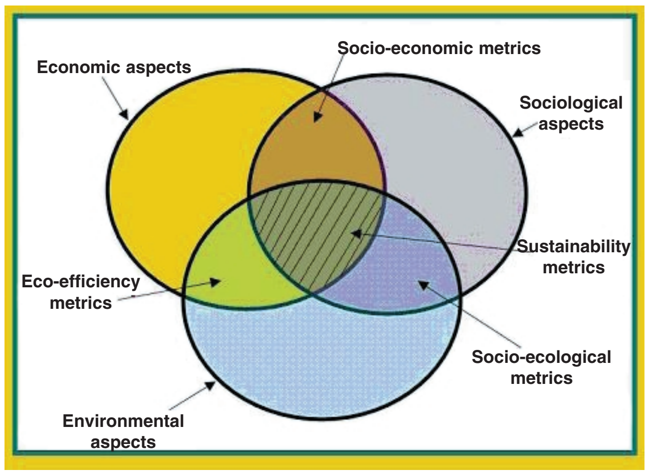

Figure 2. Three intersecting circles to illustrate sustainability.

Types of Metrics for Sustainability

Two classes of metrics are in development to indicate the state and performance of a system. These metrics are more popularly known as indicators. Those that indicate the state of a system are known as *content* indicators and those that measure the behavior of a system, *performance* indicators. The following discussion is focused on the performance indicators only, as we are mostly concerned about the means of improving the sustainability characteristics of a system. Naturally, researchers have attempted to measure improvements in terms of three groups of metrics corresponding to the three aspects of sustainability: ecological metrics, economic metrics, and sociological metrics. These metrics measure only one aspect of the system, and, therefore, are one-dimensional (1-D). There have been attempts to measure 2-D aspects as well. These 2-D metrics are shown in Figure 2 as belonging to the interactions of any two aspects of sustainability. Thus, we can identify eco-efficiency metrics, socio-ecological metrics, and socio-economic metrics. 3-D metrics can be obtained from the intersection of all three aspects, which could be called true sustainability metrics. These seven types can be summarized below (Sikdar, 2003):

Group 1 (1-D): economic, ecological, and sociological indicators

Group 2 (2-D): socio-economic, eco-efficiency, and socio-ecological indicators

Group 3 (3-D): sustainability indicators

Dozens of indicators have been suggested for use in determining improvements made to chemical processes, a manufacturing site, or a manufacturing enterprise (See Web site references for AIChE (2003) and IchemE (2003)). It would be instructive to identify them as belonging to one or another of the groups just outlined.

One of the significant studies on sustainability metrics was sponsored by the Center for Waste Reduction Technologies of AIChE for evaluating process alternatives. The metrics or indicators used in this study are material utilization, energy use, water use, toxics dispersion, pollutant dispersion, and greenhouse gas emission—all either per unit mass of product or alternatively per unit of economic value addition (Beloff et al. 2001; Schwartz et al. 2002). Given the values of these indicators for two or more processes for a product, a value judgment is made for the preferred approach. The example in Table 1 shows how two processes for making hexamethylene diamine can be compared using these metrics (Schwartz et al., 2002). The other significant effort was made under the auspices of the IChemE in the U.K. In this effort, the indicators are specifically grouped into environmental, economic, and social categories. Theirs is a comprehensive list of all possible indicators that might be relevant to a manufacturing site. The environmental indicators are further shown as belonging to either resources or environmental impact categories. Among resources the important indicators that this study suggested are energy use, material use, water use, and land use; and among environmental impacts, acidification, global warming, human health, ozone depletion, photochemical smog formation, and ecological health. Economic indicators include several value-added measures and R&D expenditures. Lastly, a range of social indicators has been proposed that are based on employee benefits, safety, and how the employees are treated in the workplace. In neither the CWRT nor the IChemE studies was any attempt made to create aggregate measures for easy comparison, for instance, for an analysis such as can be done with Figure 1. Later, we will see how we can use the three groups of metrics to classify the metrics used by AIChE and IChemE.

The only known study in the open literature on 2-D metrics development is that of BASF (Saling and Wall, 2002; Saling et al., 2002), although numerous process improvement methods have been developed that address eco-efficiency issues. BASF created the eco-efficiency indicators to measure the environmental and economic performance of a product or a process. In the BASF method, five ecological indicators are combined to provide an "ecological footprint", which is plotted against the life cycle cost of process options, and the process that has the lowest of both measures is judged to have superior eco-efficiency. BASF is reportedly developing the other two types of 2-D metrics.

Suggested Hierarchical Metrics System

We suggest below a hierarchical metrics system based on the three groups of metrics outlined above. This hierarchical metrics system will have specific applicability to Type III (business) and Type IV (processes) sustainability systems. It is based on the belief that, if we can identify true sustainability indicators (i.e., 3-D), they would more fully reveal sustainability features than the 2-D and 1-D indicators, all of which may or may not be equally important, especially at the beginning of an assessment. Besides, a hierarchical method would certainly be more cost-effective for decision-making. This idea calls for measuring the 3-D indicators first, and, if decision-making needed further elaborations, explore the 2-D and 1-D indicators, as well to address certain issues as might be important in specific situations. Because of the large variety of manufacturing cases that are possible to consider, the determination of 3-D indicators would be necessary, but not sufficient.

To identify the true 3-D indicators, we need to refer back to the accepted definition of sustainability. According to the WCED definition (WCED, 1987), the main concerns are ecological impact, economic development, and societal equity. Those indicators that directly affect these three concerns simultaneously are 3-D. Similarly, 1-D and 2-D indicators can be identified. Let us consider the prominent indicators used in the CWRT study: nonrenewable energy use, material use, waste generation, pollutant dispersion, clean water use, and cost.

Table 1. Comparing Alternative Production Processes: Metrics for Hexamethylenediamine Production**

Metric	Unit*	Hydrocyanation of Butadiene	Electrohydrodimerization of Acrylonitrile
Material	lb/$VA	1.44	0.17
Energy	kBtu/$VA	**59.4**	92.1
Water	gal/$VA	16.2	**15.4**
Toxics	lb/$VA	0.0023	**0.0000**
Pollutants	lb/$VA	0.81	**0.008**
CO_2	lb/$VA	**8.85**	13.2

- $VA=dollar value-added.·
- More-favorable metrics are shown in bold.

** Table reproduced by permission of authors (Schwartz et al., 2002).

Energy is the prime driver for economic growth, and if nonrenewable, always has an ecological impact through the emission of pollutants and greenhouse gases, and, since limited, does affect future generations. It would appear that nonrenewable energy use is inherently a 3-D indicator. Likewise, material use can have direct ecological impact, is associated with value creation, and can have intergenerational impact. Thus, material use is also a 3-D indicator. For instance, the use of bio-based materials, such as lactic acid (of which a significant portion is still produced by a synthetic method, i.e., using HCN) that could be used as intermediates for the manufacture of many useful products, since it is based on renewable material resources, could be considered to have positive social impact. Process wastes that are well controlled and contained are economic value-losses and are a 1-D economic indicator. Some wastes, such as gypsum piles, could, however, be 2-D eco-efficiency indicators, the effect being environmental nuisance and potential pollution. Pollutant dispersion is a 3-D indicator, as it represents environmental impact, has economic cost associated with it, and, frequently, has a bearing on the health of the people and ecosystems in the neighborhood of the manufacturing units. The water use could be a 1-D or 2-D indicator depending on situations. In some situations the residuals from water works could be an environmental nuisance, in which case it would be an eco-efficiency indicator, otherwise just an economic one. Lastly, the cost of manufacturing is a reflection of the nature of technology (economic value creation) and affordability for public consumption (societal value)—thus, a socio-economic indicator. In comparison, among manufacturing processes for a product, the lowest cost is not only desirable to the manufacturer for its profitability, but also intricately connected to the satisfaction of the customers. In this line of thinking, sustainable process design is a multiobjective optimization in which the cost of manufacture is minimized while improving all 3-D indicators in the first step of the design endeavor. 2-D and 1-D indicators are to be examined if and only if the 3-D ones are seen going the right way. All these considerations for just the indicators selected here are summarized in Figure 3. All other possible indicators can be similarly classified. In the light of analyzing the improvement of processes from the sustainability viewpoint, it appears that most of the CWRT metrics were 3-D and the suite of metrics was intuitively well-chosen.

The suggested hierarchical metrics systems, when properly developed, can systemize the sustainability analysis of products, processes, and enterprises. It would be particularly useful in process and product design for which the whole range of 1-D and 2-D metrics would be hard to apply. Chemical engineers are uniquely prepared for optimizing for objectives that introduce trade-offs for design options. Designing for sustainability offers the challenge of optimizing for a larger number of objectives than they have encountered in traditional practice. An increasing number of academics has made note of this special challenge recently (Batterham, 2003).

Concluding Remarks

It is important to point out that the chosen sustainability metrics should be small in number, and as independent of each other as possible. At present, no consensus exists on a reasonable taxonomy of metrics. When a consensus is reached, the need would be to find ways of consolidating the metrics in three main aggregate metrics, as required for Figure 1, which will provide a quantitative overall measure of the progress towards sustainability. Such consolidation of the metrics is difficult, however. A recognized approach of valuation (or monetization) falls under the purview of ecological economists, with whom much of the future work needs to be done in collaboration.

It is not the purpose of this article to suggest a list of a small number of metrics that could be judged as sufficient, nor is it to identify each available indicator as belonging to one or another type. Future work in this area will provide the needed clarity. It is undeniable that the interest among chemical engineers for research and education in sustainability has been on the rise. The premier chemical engineering professional societies, such as AIChE and IChemE, clearly realized that and have been pioneers in thinking about developing sustainability metrics. Recently, AIChE in its strategic planning process known as Genesis has identified sustainability as an important target of opportunity for research and education. The Institute for Sustainability, which is in the formative stage within AIChE, and the recently formed Sustainable Engineering Forum, will underscore the opportunities for much discussion on sustainability and sustainability metrics in the near future.

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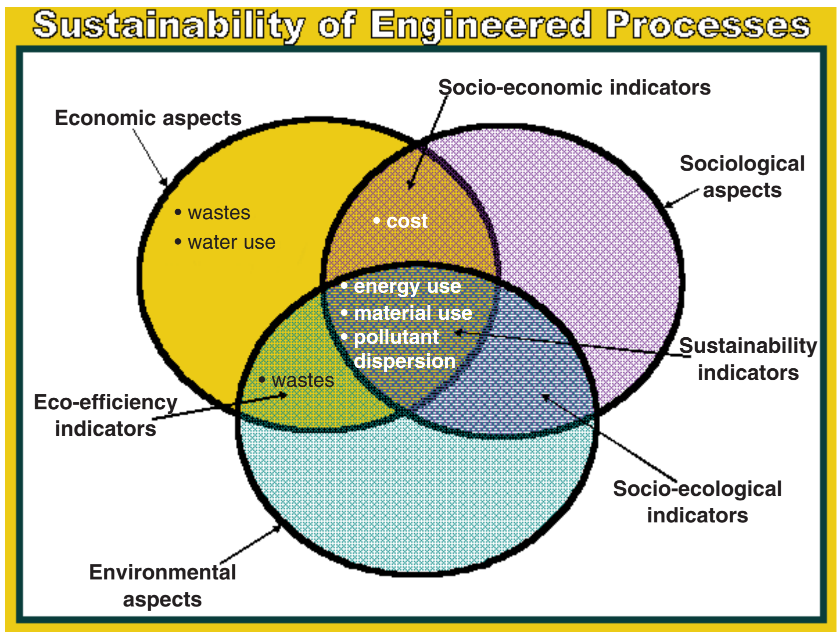

Figure 3. Hierarchical metrics system.

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