**METRICS AND INDICATORS FOR SUSTAINABLE MANUFACTURING**

**Introduction**

Indicators (or metrics) measure aspects of a system that allow us to characterize the conditions of the system. The values of indicators assist in effective decision-making, such as business decisions to build or extend a new chemical plant, performance improvement decisions for a reactor, or government policy-making related to environmental pollution from a particular sector. Indicators are also essential for evaluating current conditions by tracking outcomes of actions taken or assessing progress toward overall goals by calibrating progress toward such goals. They can provide an early warning to prevent economic, social, and environmental setbacks. The goal of this module is to provide an overview of the metrics compiled by two of the most significant professional societies in chemical engineering, AIChE and IChemE. This background will provide the necessary indicators that one must compute in order to achieve sustainability of manufacturing systems.

The selection of indicators effectively determines the “looking glass” through which one views the technical or policy options within a system; therefore, it is extremely important in influencing decisions and judgments. Needless to say, the first hurdle in effective decision-making is the choice of the indicators that best represent a system. Once a set of specific indicators for a system assessment is chosen, data collection for those indicators may pose difficulties. The final step is decision making with the indicator values. Combining the three pillars of sustainability and finding a single value that encompasses the comprehensive set of indicators is a daunting, but necessary task to incorporate physical and social science knowledge into decision making. The decision making with indicators is covered in a separate module.

**Rationale: Use of Metrics and Indicators for Sustainable Manufacturing**

As stated above, the use of metrics and indicators are prevalent for tracking the progress of a system. However, a consensus does not exist on which is the best set of indicators for a particular system, nor is such universal guidance provided for manufacturing systems. From limited literature, even if such metrics are available, they track particular aspects of sustainability individually, without any criteria given for arriving at decisions using such indicators. This module aims to identify the different systems that a manufacturing process encounters, narrow the set of indicators specific to a manufacturing system and distinction from its surroundings, followed by a methodology to calculate the Sustainability Footprint of the manufacturing system by computing an aggregate index. Thus, to effectively measure progress towards sustainability, a sustainability footprint assessment method is explained in this module, which aids in decision making with indicators and metrics for a sustainable manufacturing system. Learning outcomes from this module will help in effective and comprehensive decision making with indicators for sharing information with stakeholders.

**Course Content: Metrics and Indicators Theory, Relevant Sustainability Metrics**

***Indicator Types***

The indicators measuring sustainability of a system vary according to the scale of that system. For example, the comparative progress of a country over another towards sustainable development can be partly measured by the percentage of population having access to clean drinking water. The sustainability of a chemical process compared to another can be partly determined by the amount of material it uses or the amount of greenhouse gases it generates. Thus, sustainability analysis always involves a relative measure comparing one system to a reference system. The reference system can be another competing system or a synthetic one, or even the same system in a different time in the past.

In the context of sustainable manufacturing, the systems that need to be considered are at either technological or business scales, i.e. Type III or Type IV systems explained by Sikdar, 2003.

“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.”

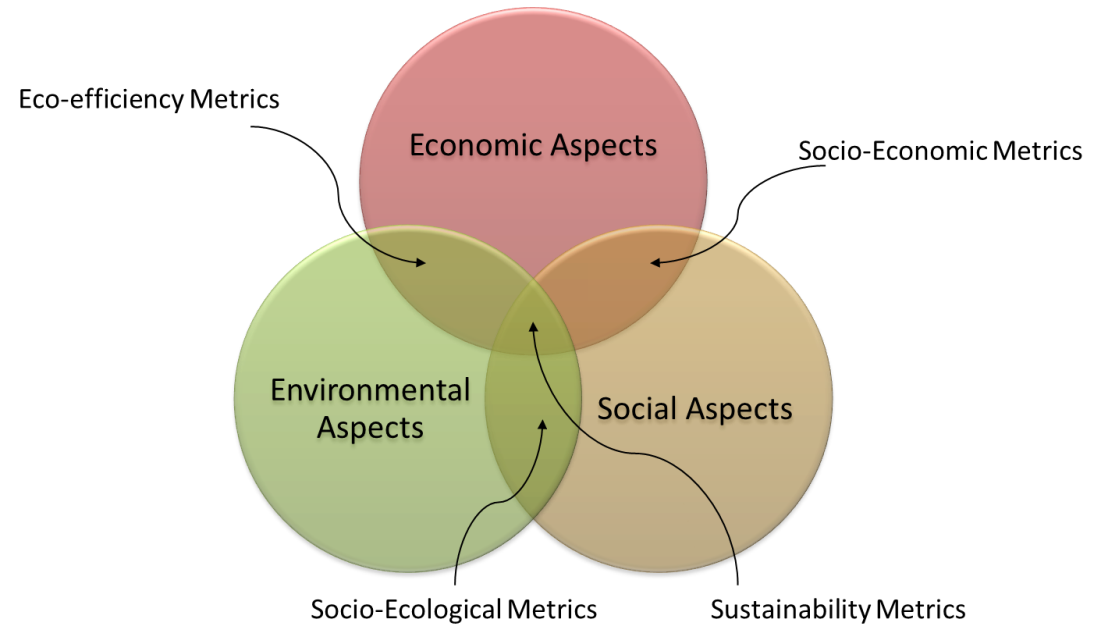


Figure 1. The venn-diagram to represent sustainability of systems

Metrics or indicators are of two types, *content* indicators and *performance* indicators. Content indicators measure the state of a system and performance indicators measure the behavior of a system. For sustainability in general and sustainable manufacturing in particular, performance indicators are assessed as the primary concern is to improve the sustainability characteristics of a system. For sustainability assessment, improvements are measured in terms of three groups of metrics corresponding to the three aspects of sustainability: ecological metrics, economic metrics, and sociological metrics. Figure 1 shows the three dimensions of sustainability, and the metrics measuring only one aspect of the system are known as one-dimensional (1-D) metrics. When indicators measure any two dimensions of sustainability simultaneously, they are known as 2-D 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

Over the years, various institutions have made progress in assessing the relative sustainability of particular systems of interest. The most significant and relevant methods are reviewed in this module. It must be noted that the work from these institutions are the cumulative effort from several researchers and organizations working together to bring a set of metrics that can be universally accepted. Also, since the definition of sustainability metrics is still a work in progress and no standards currently exist, often the clear distinction of 1-D, 2-D and 3-D metrics is not made. These metrics are called ‘sustainability’ metrics when they may be just environmental or socio-ecological metrics.

A user may choose to compute all or some of these indicators, depending on the available resources. However, it must be warranted that the exclusion of indicators may leave important metrics that will not give the true picture of sustainability.

***AIChE Sustainability Metrics Suite/ BRIDGES to Sustainability Metrics***

One of the earliest studies in the development of sustainability metrics for decision making was conducted by Canada’s National Round Table on the Environment and the Economy (NRTEE) ([Tanzil et al., 2003](#_ENREF_40)). This study by NTREE included eight companies from different sectors, and recommended a set of core metrics which included material intensity, energy intensity, and dispersion of regulated toxics per unit of products or services. This study also suggested the use of complementary metrics such as greenhouse gas intensity. The World Business Council for Sustainable Development (WBCSD) recommended that in addition to the material and energy consumptions, water consumption is another important sustainability metric. WBCSD also identified the emissions of greenhouse gases and ozone-depleting substances as the metrics having an environmental impact that can be calculated based on existing international consensus. The Center for Waste Reduction Technologies (CWRT) of the American Institute of Chemical Engineers (AIChE) (currently the Institute for Sustainability, AIChE) with representatives from member companies was instrumental in developing sustainability metrics further (Beloff and Beaver, 2000). This effort concluded on a set of basic and complementary sustainability metrics expressed on a choice of denominators that include mass, revenue, or value added. BRIDGES to Sustainability™, a not-for-profit organization compiled all of this information and developed an automated methodology and software known as BridgesworksTM (Schwarz et al., 2002, Tanzil et al., 2003). BRIDGES conducted the research on the metrics development with significant funding from the U.S. Dept. of Energy under a cooperative agreement with AIChE’s CWRT.

Table 1. Basic sustainability metrics ([Tanzil et al., 2003](#_ENREF_40))

|  |  |
| --- | --- |
| **Output:**  Mass of Product  or  Sales Revenue  or  Value-Added | **Material Intensity** |
|  |
| **Water Intensity** |
|  |
| **Energy Intensity** |
|  |
| **Solid Waste to Landfill** |
|  |
| **Toxic Release** |
|  |

Basic and complementary metrics under six impact categories were chosen to represent: material, energy, water, solid wastes, toxic release, and pollutant effects. The five basic indicators corresponding to these categories were: material intensity, energy intensity, water consumption, toxic emissions, and pollutant emissions (Table 1). These ratios are constructed with environmental impacts in the numerator and a physically- or financially-meaningful representation of output in the denominator. A process which has a smaller value for the metric in Table 1 is the better process. These metrics have been used in various manufacturing facilities like Formosa Plastics (petrochemical), Interface Corporation (carpeting) and Caterpillar Inc. (tool manufacturing). Examples of complementary metrics related to the six impact categories are given in Table 2.

Table 2. Examples of complementary sustainability metrics ([Tanzil et al., 2003](#_ENREF_40))

|  |  |
| --- | --- |
| Indicator | Metric for measuring the indicator |
| **Material** | Packaging materials  Non-renewable materials  Toxics in product  Toxics in raw materials |
| **Water** | Rainwater sent to treatment  Water from endangered ecosystem sources  Water use relative to water availability |
| **Energy** | Energy consumed in transportation  Non-renewable energy |
| **Solid waste** | Solid waste disposed relative to landfilling capacity |
| **Toxic release** | Toxic release under each TRI category  Human toxicity (carcinogenic)  Human toxicity (non-carcinogenic)  Ecosystem toxicity |
| **Pollutant effects** | Global warming potential  Tropospheric ozone depletion potential  Photochemical ozone creation potential  Air acidification potential  Eutrophication potential |

***Institute for Chemical Engineers: IChemE Sustainable Development Process Metrics***

The Institution of Chemical Engineers (IChemE) compiled a list of sustainable development process metrics for use by companies to report on their advancement towards sustainability (IChemE, 2014). These metrics allow for the comparison of different options within a company, or compare between companies. This method was developed both for assessing sustainability of corporations and individual technologies, but it is important that even for small operating units the wider implications and impacts are considered through this method. The metrics for the sustainable development include environmental, economic and social indicators, as shown in Table 3.

Table 3.The IChemE Sustainable Development Process Metrics (IChemE, 2014)

|  |  |  |
| --- | --- | --- |
| Indicator Type | Category | Metrics |
| Environmental indicators | Resource usage | Energy  Material (excluding fuel and water)  Water  Land |
| Emissions, effluents and waste | Atmospheric impacts  Aquatic impacts  Impacts to Land |
| Additional environmental items | Duty of care with respect to products and services produced for which environmental or health problem solutions are not yet known.  Environmental impact of plant construction and decommissioning.  Compliance  Impacts on protected areas  Impacts on local biodiversity or habitats  Issues concerning long-term supply of raw materials from non-renewable resources.  Other possible relevant metrics. |
| Economic indicators | Profit, value and tax | - |
| Investments | - |
| Additional economic items | - |
| Social indicators | Workplace | Employment situation  Health and safety at work |
| Society | - |
| Other items | Issues concerning discrimination, concerning women and minorities or indigenous communities, the number in senior and middle management Programmes to improve employability including focused education or training, and mentoring  Incidents of child labour, forced labour or violation of human rights, on the part of the company, its suppliers or contractors, and public protest concerning such issues. Report positive steps taken in this regard.  Performance of suppliers and contractors relative to criteria for their selection. Incidents of non-compliance with sustainability requirements, eg Responsible Purchasing.  Other possible relevant metrics |

The IChemE sustainable development progress metrics are described in details with the equations required to compute the indicators in their report (IChemE, 2014). A company wishing to disclose their sustainability performance is required to use these indicators, collect data for them, and compile the indicator values in a prescribed report format. Thus, the IChemE metrics help to collect information on the various aspects of process related sustainability for a given company for external reporting. Internally, a particular company may make use of the indicators to compare between several competing processes. The report in itself is a just a compilation of indicator data and two companies or processes are compared on a particular indicator on an ad hoc basis. **Connections to Existing Core Curriculum**

The inclusion of metrics for sustainability indicators is crucial for current courses. Typically, these indicators span across a variety of subjects, such as basic chemical engineering material and energy balances, environmental engineering, process safety, engineering design etc. Students need to make a connection between the metrics and the substance flows that allow the calculation of such metrics. Also courses on life cycle assessment, sustainability in general need to include such topics on metrics calculation because that quantifies the quest for sustainability assessment.

**References for Further Reading**

Beloff, B., Beaver, E., (2000), Sustainability Indicators and Metrics Project of CWRT. Bridges to Sustainability, Houston, TX

Fiksel, J, Eason, T., Frederickson, H., (2012), A framework for sustainability indicators at EPA. *National Risk Management Research Laboratory Office of Research and Development US Environmental Protection Agency* .

IChemE, (2014), The Sustainability Metrics—Sustainable Development Progress Metrics Recommended for Use in the Process Industries. Institution of Chemical Engineers, Rugby, UK.

Jain, R, (2005), Sustainability: metrics, specific indicators and preference index. Clean Technologies and Environmental Policy 7.2 : 71-72.

Martins, A. A., Mata, T. M., Costa, C. A., Sikdar, S. K., (2007), Framework for sustainability metrics. Industrial & engineering chemistry research, 46(10), 2962-2973.

Schwarz, J., Beloff, B., Beaver, E., (2002), Use sustainability metrics to guide decision making. Chem. Eng. Prog. 98, 58\_63.

Sengupta, D., Mukherjee, R., Sikdar, S.K., (2015), Chapter 4 - Moving to a decision point in sustainability analyses, In: Assessing and Measuring Environmental Impact and Sustainability, edited by Jiří Jaromír Klemeš, Butterworth-Heinemann, Oxford, Pages 87-129, ISBN 978012799968

Sikdar, S.K., (2003), Sustainable development and sustainability metrics. AIChE J. 49, 1928\_1932.

Tanzil, D., Ma, G., Beloff, B., (2003), Sustainability metrics. Innovating for sustainability. The 11th International Conference of Greening of Industry Network, San Francisco, CA, USA, pp. 12\_15.