Development Overview of Sustainable Manufacturing Metrics

Shaw C. Feng[1], Che-Bong Joung[1], and Gang Li[2]
[1]Manufacturing Engineering Laboratory, National Institute of Standards and Technology (NIST), Gaithersburg, Maryland, USA
[2]Hefei University of Technology, Hefei, Anhui, China

Abstract

The manufacturing industry is facing the challenge of measuring sustainability performance in a product's life cycle. Developing metrics for sustainable manufacturing is critical to enable manufacturing companies to quantitatively measure the sustainability performance in specific manufacturing processes. This paper describes the development of an infrastructure for measuring the sustainability of a product in its entire lifecycle. The performance includes environmental, economical, and social benefits in stock material preparation, manufacturing, distribution, customer use, and post use. Infrastructural components include sustainability metrics repository, measurement methods, guidelines, and sustainability performance analysis and reporting tools. The sustainability measurement infrastructure provides a foundation for decision-making and is expected to be tightly integrated into a company's business strategy development processes.

Keywords

Performance Measurement, Sustainability Indicator, Sustainability Measurement Infrastructure, Sustainability Metrics, and Sustainable Manufacturing.

1 INTRODUCTION

As the manufacturing industry is facing challenges of global resources depletion, climate change, environmental pollution, and economic stagnation, manufacturing companies are under pressure to cope with the problems and maintain competiveness. Sustainable manufacturing has been proposed to enable companies moving in the direction of competitiveness to meet the challenges facing industrialized countries. The measurement of sustainability in manufacturing is an enabler to quantitatively measure the sustainability performance in specific manufacturing processes. The Organisation for Economic Co-operation and Development (OECD) has a project to "develop a toolkit to help business benchmark performance and improve their production processes and products [1]." The American Small Manufacturers Coalition (ASMC) identifies a critical threat to U.S. manufacturing that sustainability measurement systems are inadequately deployed [2].

Addressing these industry needs, we propose a measurement infrastructure to measure sustainability in products and manufacturing processes, described in this paper. First, we describe the foundation of developing the infrastructure, consisting of definitions on a set of fundamental terms frequently used in sustainability measurement, characteristics of the sustainability measurement, and the statement of the purpose. Next, we describe the current state of sustainable manufacturing metrics in research and development. Lastly, based on the available methods, we describe measurement processes of sustainability in the product lifecycle and the organization that the product is made. We also provide an overview of infrastructural components in this paper.

2 FOUNDATION FOR DEVELOPING A SUSTAINABILITY MEASUREMENT INFRASTRUCTURE

Meaningful sustainability performance measurement is based on well-defined indicators and a clear statement of the purpose of the measurement. To lay a foundation for the development of an infrastructure, this section provides definitions related to sustainability, indicator, the indicator's characteristics, and the purpose of measurement

2.1 Definitions

There are many different definitions on sustainability at both conceptual and technical levels. To be consistent, this paper provides several necessary definitions as the basis for discussion in the rest of the paper. First, *Sustainable development* is a pattern of resource use that aims to meet human needs while preserving the resource use and the environment so that these needs can be met not only in the present but also for future generations. The term was used by the Brundtland Commission, which coined what had become an often-quoted definition of sustainable development that "meets the needs of the present without compromising the ability of future generations to meet their own needs [3]." Sustainable development is a goal as long as there is a lack of standard metrics and benchmark values to measure the performance of sustainable development. Second, *Sustainability in development* is an organization's ability to advance its economic state without compromising the environment and the social equity that provide the quality of life for all community residents, present or future. Third, United States Department of Commerce defined *Sustainable Manufacturing* as the creation of a manufactured product with processes that have minimal negative impact on the environment, conserve energy and natural resources, are safe for employees and communities, and are economically sound [4]. The manufactured product is designed with considerations of the product's entire life cycle, including the manufacturer's economic benefits, and its full impact on the environment and the society. Lastly, we provide definitions for several technical terms. *Parameter* is a property that is measured or observed [5]. An example would be the quantity of CO_2 in kg. *Indicator* is a parameter which points to, provides information about, or describes the state of a phenomenon/environment/area, with a significance extending beyond that directly associated with a parameter value [5]. An indicator is a specific expression that provides information about an organization's environmental performance, efforts to influence that performance, or the condition of the environment. An example would be that the CO_2 parameter is used as an

indicator to indicate the quantity of CO_2 emitted by a factory in a year. *Performance Metric* is a standard means of measuring and tracking an indicator. It can be measured in quantitative or qualitative ways. Measured result can be an absolute or a relative value, and a normalized or a non-normalized number. An example would be that the CO_2 indicator is chosen by the factory management as a performance metric to show the reduction in CO_2 emission. *Index* is a value calculated from a set of performance metrics with a specified algorithm. An example would be that an index of CO_2 emission of a company is the aggregation of all the CO_2 indicators in that company. *Benchmark Value* can be defined as a targeted value of an indicator. An example would be that the limit of the quantity of CO_2 in kg emitted by a factory in a year is chosen by the factory management to limit the CO_2 emission from the factory.

2.2 Sustainable Performance Metrics Characteristics

Well defined performance metrics for the manufacturing industry have the following characteristics:

- *Measurable*: Indicator must be capable of being quantitatively measured in a phenomenon that is of a sustainability concern, e.g., economic benefit, social well being, environmental friendliness, and technical advancement.
- *Relevant* and *Comprehensive*: Indicator must provide useful sustainability information on manufacturing processes. It must fit the purpose of measuring performance and addressing all of the organization's major aspects and objectives.
- *Understandable* and *Meaningful*: Indicator should be easy to understand by the community, especially, for those who are not experts.
- *Manageable*: Indicators are limited to the minimal number required to meet the measurement purpose. At the same time, the organization should be allowed to make the decision on the number and type of indicators to apply [6].
- *Reliable*: Information provided by indicator should be trustworthy. It can address inputs (leading indicators) and outcomes (lagging indicators) of a process [7].
- *Cost-Effective Data Access***:** Indicator has to be based on accessible data. The information needs to be available or can be gathered when it is necessary from existing sources or otherwise easily collected.
- *Timely manner*: Measurement takes place with the frequency to enable timely, informative decision-making [6].

2.3 Why measure sustainability

The number of manufacturing companies that demand the ability to measure sustainability in their products and processes is rapidly increasing. The abilities that companies are seeking can be summarized as follows:

- *Sustainability accounting*: Resource utilization, waste generation, pollution emission from all activities in manufacturing should be evaluated and documented for sustainability performance evaluation.
- *Impact analysis*: the impacts on people's well being, on the environment, and on the economy by the manufacturing activities should be evaluated against industry benchmark values using predefined sustainable performance metrics to observe the trend of sustainability performance.

Based on these efforts, manufacturing companies could implement their own sustainable manufacturing environment by achieving the following specific objectives:

- Waste elimination
- Energy efficiency
- Product designed for disassembly, reuse, and recycle
- Habitat conservation
- Zero consumption of non-renewable resources

3 CURRENT STATE OF METRICS DEVELOPMENT

There are many international initiatives that have developed guidelines, recommendations, and indicator sets related to reporting sustainability and environmental concerns. Their application domains are primarily on company, regional, national, and global levels. The requirements for measuring manufacturing processes and manufactured products have not yet been fully addressed.

3.1 Available sustainability indicator set

A summary of publicly available sets of sustainability and environmental indicators is as follows:

- *Dow Jones Sustainability Index (DJSI)* [8]: Dow Jones Sustainability Indexes are used to assess the financial and sustainability performance of the top 10% of the companies in the Dow Jones Global Total Stock Market Index. The assessment is divided into three distinct sections with 12 criteria, covering the economic, environmental and social dimensions and including answers from the questionnaire as well as the results from a media and stakeholder analysis.
- *OECD Core Set of Environmental indicators* (*OECD Env*) [9]**:** OECD Core Set of environmental indicators are linked to the monitoring of environmental conditions and trends. It includes about 50 indicators, which cover a broad range of environmental issues and economic data to track pressures on the environment and responses by governments, industry and households.
- *OECD Toolkit* [10]**:** The intent of the toolkit is to provide a moderate level of technical expertise for small and medium companies. The focus of the toolkit is on the calculation and interpretation of 18 core indicators of sustainability performance in terms of materials and processes.
- *Ford Product Sustainability Index* (*FORD's PSI*) [11]: Ford's PSI considers environmental, economic and societal aspects based on externally reviewed environmental and cost aspects, such as a Life Cycle Assessment (LCA) and life cycle cost analysis, and other relevant aspects, including sustainable materials, safety, mobility capability and noise. Ford's PSI is split into 8 indicators.
- *General Motors Metrics for Sustainable Manufacturing* (*GM M4SM*) [12]: General Motors defined the project as a review of state-of-the-art metrics for sustainable manufacturing. The goal of the project is to determine which metrics for sustainable manufacturing should be recommended for implementation. Based on that project, the company recommends over 30 metrics under 6 major categories: environmental Impact, Energy consumption, personal health, occupational safety, waste management, and manufacturing costs.
- *Environmental Pressure Indicators for the European Union* (*EPI-EU*) [13]: EPI-EU is the result of the Environmental Pressure Indices project, which aims to give a comprehensive description of the most important human activities that have a negative impact on the environment. The EPI-EU contains 60

indicators giving an overview of the pressure of human activities on our environment in 10 policy fields. They cover air pollution, climate change, biodiversity, and dispersion of toxic substances.

- *United Nations Commission on Sustainable Development Indicators* (*UN-CSD*) [14]: UN-CSD indicators contain a core set of 50 indicators under 14 different themes, reviewed by an expert group in 2006. Based on the review, the group provides guidance on applying and adapting the UN-CSD indicators for the development of national indicator sets.
- *Walmart Sustainability Product Index Questions* (*Walmart Qs*) [15]: Walmart has announced plans to develop a worldwide sustainable product index with 15 questions to suppliers. The company expects to help customers to make purchase decisions and to encourage suppliers to meet sustainability requirements. Unlike others, no technical detail has yet become available.

Some other initiatives have been summarized in previous papers [16, 17, 18]: Life Cycle Assessment (LCA), Ecological Footprinting (EF), ISO 14031, Material Flow Analysis (MFA), Pollutant Release and Transfer Registries (PRTRs), EU's Environmental Management and Audit Scheme (EMAS), Global Reporting Initiative (GRI), Materials Input per Unit Service (MIP), and Intergovernmental Panel on Climate Change (IPCC).

3.2 Needs of new performance metrics

From the review of currently available sets of sustainability indicators, we extend Bordt's work [10] to show the effectiveness of all major global initiatives on metrics development at different technical detail levels and domains, as shown in Figure 1. The indicator sets reviewed in section 3.1 are in almost all the measurement units and in medium and low levels of technical details. Most indicator sets are for reporting sustainability of a company, such as GRI, DJSI, ISO 14031, Wal-mart questions, and UN-CSD. Others are for reporting environmental indicators, such as OECD Env., IPCC, EU EMAS, and EPI-EU. Only two are related to products, and they are OECD Toolkit and Ford's PSI. The level of technical details on them is medium. The development of metrics for sustainable products and processes has not been fully addressed; however, a wide range of manufacturing companies have demanded sustainability metrics for products and processes. The NIST development effort has the focus on such sets of metrics to measure sustainability performances in products and processes.

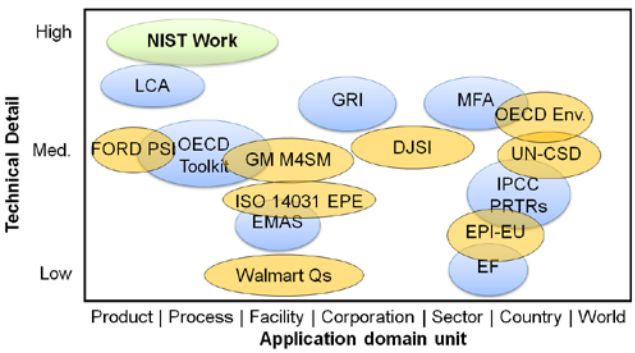


Figure 1. Existing metrics and their effective application domains (based on [10])

4 AN OVERVIEW OF THE MEASUREMENT INFRASTRUCTURE

The review of indicator sets and the categories of indicators above are for specific companies or for countries to report sustainability performance. There is a lack of an open, neutral, inclusive, and harmonized set of indicators and indices for sustainable manufacturing. A sustainability measurement infrastructure is being developed at NIST.

4.1 Indicator/index placement

The placement of an indicator or index for measuring a sustainability parameter has been an issue. There are two domains that an index can be measured for sustainability performance. They are (1) lifecycle activities and (2) levels in an organization.

In a product lifecycle, activities include (1) mining for raw materials from Earth, such as metal ores, (2) processing raw materials into stock materials, such as extracting Aluminium from Bauxite and making Aluminium stocks, (3) manufacturing, i.e., transforming stock materials into products, (4) distributing manufactured products to end users, including packaging, storage, and delivery, (5) use, including service, maintenance, and repair, and (6) post-use processing at the end of the service life of the product, including remanufacturing, repair, reuse, recycle, and disposal.

Figure 2 shows an example of using CO_2 emission as an indicator throughout a product's lifecycle. In the example, the indicator is applied to all the activities in the product lifecycle. Various amounts of CO_2 emission in individual activities are measured and plotted on the chart. The total emission in the whole lifecycle of the product is the sum of the amounts of all the activities associated with the product in its lifecycle.

From an organizational point of view, an indicator can be placed at different levels of an organization. Most organizations have a hierarchical structure. For example, in a manufacturing facility, there are levels of machine, work cell, assembly or product line, factory, company, and supply chain. Figure 3 shows some example indicators at various levels and the aggregation of the value of an indicator from a low level to high levels in a manufacturing organization. In Figure 4 (a), indicators used in sustainability measurement of a manufacturing process include restricted substance, package material reuse, CO_2 emission, energy efficiency, employee health, safety, fresh water use, and wastes generation. Some components may be purchased from an outside source. A delivered component needs to have measured sustainability known to the customer. Figure 4 (b) shows example indicators used in measuring a delivered

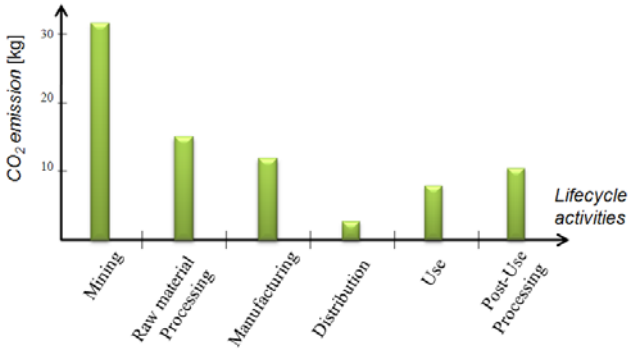


Figure 2. CO_2 emission of a product's life cycle (an example)

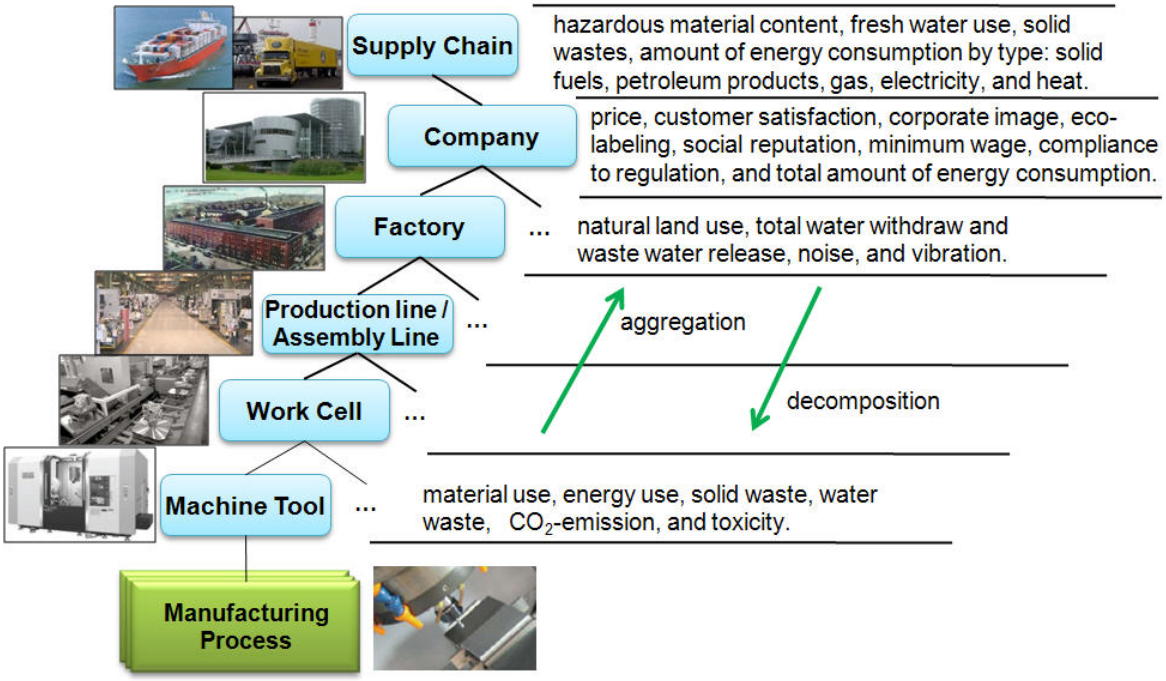


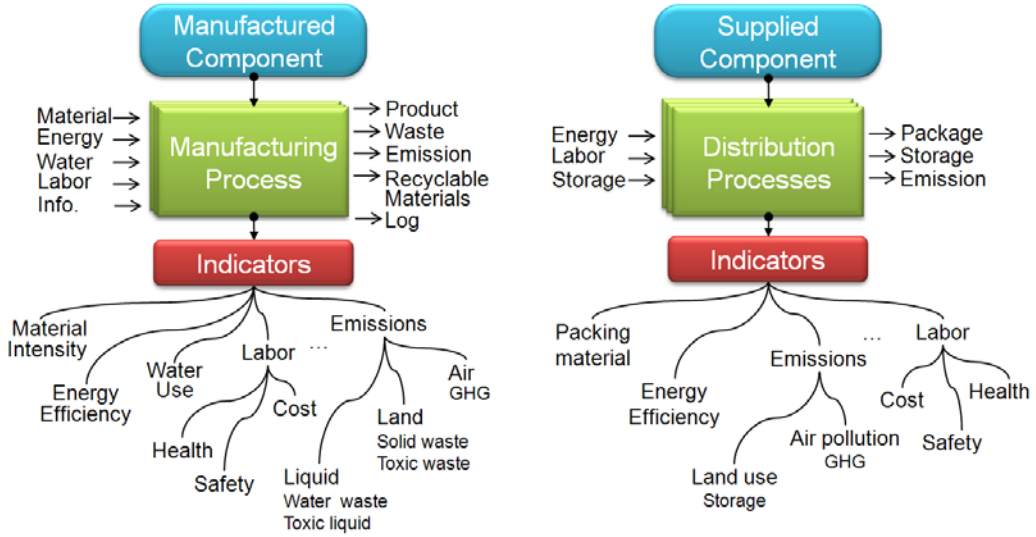
Figure 3. Indicator examples on various levels in an organization

component from a supplier.

4.2 Key Infrastructural components

The sustainability measurement infrastructure that NIST is developing includes the following key components:

- *Indicator Repository*: It contains a comprehensive set of necessary sector-specific multi-dimensional indicators, representing the sustainability of the manufacturing systems. Benchmark values are provided in this repository as well. Sustainability indicators and metrics in the repository can be adapted from sets reviewed in section 3.1, or can be derived from standards, such as ISO 14301 [19]. Indicators can be grouped and organized in various ways. The organization of indicators determines the effectiveness of sustainability performance. Suggested Indicator hierarchies, which will be developed using a structure of categories and the relationship with the product life cycle, are also parts of the repository. Example categories have been shown in previous works [16, 17, 18, 20].
- *Measurement Guidelines*: The main purpose of sustainability measurement is for internal decision-making and external accountability reporting; thus, sustainability measurement process must contain the information not only about the measurement process but also the measurement purpose. A measurement process includes operations, instrument, tools, associated indicators or indices, related objectives, and benchmark values, according to the business strategies. The sustainability measurement process is usually realized by three phases: plan, implement, and review [21]. The prerequisite for quality in sustainability measurement is that measuring methods should be based on standard procedures, commonly accepted terminology, instrument certifications, and standard reference materials.
- *Analysis & Reporting tools*: Performance evaluation analysis and reporting tools are necessary for business decision making to maintain sustainability.



(a) Component in process (b) Delivered component

Figure 4. indicators used in sustainability measurement

Engineers use analysis tools to process measured values and analyze the trend and evaluate the measured value against the benchmark value to determine the performance. Management uses reporting tools to communicate with various stakeholders, internal and external, on results from the analysis.

5 SUMMARY AND FUTURE WORK

This paper provides the description of a critical need for performance measurement infrastructure for sustainable manufacturing. The paper has also introduced an initial development of an infrastructure for sustainability performance measurement and management. The infrastructure includes indicator repository, measurement process, and performance analysis and evaluation. In developing the indicator repository, available indicators and their categories are reviewed in Section 3. There are at least two types of application domains of metrics. They can be applied to both product lifecycle and the level of the organization that produces the product. Other key components in the measurement infrastructure support the measurement of sustainability performance in products and processes for manufacturing companies. The future work includes establishing industry collaboration to enhance and validate indicators, deployment and implementations, constructing a testbed and software tools development for analysis and evaluation of sustainability in products and processes.

DISCLAIMER

No approval or endorsement of any commercial products by the National Institute of Standards and Technology (NIST) is intended or implied. Certain company names are identified in this paper to facilitate understanding. Such identification does not imply that their products are necessarily the best available for the purpose of sustainability.

REFERENCES

[1] OECD, 2009, Policy Brief (June 2009): Sustainable Manufacturing and Eco-innovation: Towards a Green Economy, http://www.oecd.org/dataoecd/34/27/42944011.pdf.

[2] ASMC, 2009, News release, June 11, 2009, http://www. smallmanufacturers.org/picts/ASMC-National-NGM-Study-News-Release.pdf.

[3] Harris, J., Wise, T, Gallagher, K, and Goodwin, N. (Eds.), 2001, A Survey of Sustainable Development: Social and economic dimensions. Island Press: Washington.

[4] DoC, 2009, How does Commerce Define Sustainable Manufacturing, http://www.trade.gov/competitiveness/sustainablemanufacturing/how_doc_defines_SM.asp.

[5] OECD, 2005, Measuring Sustainable Development: Achievements and Challenges, SG/SD/RD(2005)3, OECD, Paris.

[6] Jackson, T. and Roberts, 2000, P., A REVIEW OF INDICATORS OF SUSTAINABLE DEVELOPMENT: Report of Scottish Enterprise Tayside, http://www.trp.dundee.ac.uk/library/pubs/set.html#4.7.

[7] Sustainable Measures Web site, 2009, http://sustainable measures.com.

[8] Dow Jones, Accessed 2009, Dow Jones Sustainability Index, http://www.sus tainabilityindex.com/07_htmle/publications/guidebooks.html.

[9] OECD, 2000, Part B - Environmental Performance Indicators, OECD Rome Conference Proceedings-Volume II: Framework s and indicators, pp.99 - 127.

[10] Bordt, M., 2009, OECD Sustainable Manufacturing Toolkit, Sustainability and U.S. Competitiveness Summit, U.S. Department of Commerce, October 8, 2009.

[11] Ford, 2009, Ford Product Sustainability Index, http://www.ford.com/doc/sr07-ford-psi.pdf.

[12] Dreher, J., Lawler, M., Stewart, J., Strasorier, G., and Thorne, M., 2009, General Motors Metrics for Sustainable Manufacturing, MIT Sloan School of Management report, Cambridge, Massachusetts, May 14, 2009.

[13] EuroStat, 1999, Towards Environmental Pressure Indicators for the European Union (EU), an EU report, Brussels, Belgium, 1999.

[14] United Nations Committee on Sustainable Development, 2007, Indicators of Sustainable Development: Guidelines and Methodologies (3rd Eds.), United Nations, New York.

[15] Wal-mart, 2009, Sustainability Product Index, http://walmartstores.com/download/3863.pdf.

[16] Liu, Z., Li, B., Huang, H., and Zhang, H., 2008, “Research on Quantitative Assessment Methods of Environmental Performance in Green Design,” the proceeding of The 15th CIRP International Conference on Life Cycle Engineering, March 2008, Sydney, pp. 136 - 141.

[17] Jawahir, I., Badurdeen, F., Gupta A., and Jayal, A., 2009, Towards Developing Metrics for Sustainable Manufacturing, Proceedings of the 7th Global Conference on Sustainable Manufacturing, IIT Madras, Chennai, India, pp. 27 - 37.

[18] Singh, R., Murty, H., Gupta, S., and Dikshit, A., 2009, An overview of sustainability assessment methodologies, Ecological Indicators, vol. 9, no. 2, March 2009, pp. 189-212.

[19] ISO, 1999, Environmental management-Environmental performance evaluation-Guidelines, ISO 14031:1999(E).

[20] Feng, S. and Joung, C., 2009, An Overview of a Proposed Measurement Infrastructure for Sustainable Manufacturing, Proceedings of the 7th Global Conference on Sustainable Manufacturing, IIT Madras, Chennai, India, pp. 355-360.

[21] Fiksel, J., McDaniel, J. and Mendenhall, C., 1999, Measuring Progress Towards Sustainability: Principles, process, and best practices, Greening of Industry Network Conference; Best Practice Proceedings, Battelle Memorial Institute, Life Cycle Management Group Columbus, Ohio.

CONTACT

Shaw C. Feng

Manufacturing Systems Integration Division,
Manufacturing Engineering Laboratory,
National Institute of Standard and Technology,
Gaithersburg, Maryland 20899, USA.
Email: shaw.feng@nist.gov