Summary of the NIST Workshop on Sustainable Manufacturing: Metrics, Standards, and Infrastructure

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Abstract

This paper summarizes the presentations, discussions, and recommendations of the National Institute of Standards and Technology (NIST) Workshop "Sustainable Manufacturing: Metrics, Standards, and Infrastructure" held at NIST, Gaithersburg, Maryland, USA, October 13th through October 15th, 2009. The primary objective of this workshop was to bring together experts and various stakeholders to identify and discuss measurement and standards enablers that positively affect the social, economic, environmental, and technological aspects of designing sustainable production processes and products. The workshop was well attended and consisted of thirty presentations organized under five sessions: 1) Government Initiatives; 2) Industry Perspectives; 3) University Research; 4) Non-Government Organizations (NGOs) research; and 5) Solution Provider's Views. Two breakout sessions and an industry panel provided a set of recommendations for addressing critical issues in sustainable manufacturing.

1. Introduction

Next generation product design and manufacturing will be strongly influenced by life cycle environmental impacts and resource depletion. Hence, sustainable manufacturing[1] practices will play an important role in "meeting the needs of the present without compromising the ability of future generations to meet their own needs[2]." Sustainable manufacturing is causing companies to implement new design and analysis procedures, energy reduction methods, material reduction efforts, and improved materials handling practices. Thus, minimizing environmental impact has become a critical manufacturing industry requirement throughout the product life cycle. To foster sustainable practices, there needs to be a *measurement methodology* to assign the energy and environmental cost at each stage in that life cycle. Information must be available at the early design stage about the ultimate costs of each design decision for a new product, and the decisions themselves must be available at the end of product life to ascertain how to properly dispose of or reclaim the components.

Ensuring a sustainable future requires an integrated system of systems approach. Interlinked pathways of interaction at various levels characterize such systems. These levels span technical,

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[1] Sustainable manufacturing is a systems approach for the creation and distribution (supply chain) of innovative products and services, that: minimizes resources (inputs such as materials, energy, water, and land); eliminates toxic substances; and produces zero waste that in effect reduces green house gases, e.g., carbon intensity, across the entire life cycle of products and services.

[2] Our Common Future: Report of the World Commission on Environment and Development, Oxford University Press, 1987.

economic, ecological, and societal issues. The interactions within and across these levels are critical to the fundamental understanding of sustainable design and manufacturing, because tackling any one of the issues in isolation could result in unintended consequences.

The systems approach of sustainability requires life cycle thinking. The life cycle of a product starts with raw material extraction and processing, continues with the pre-design and fabrication of the relevant semi-finished products, includes manufacturing and assembly of the final product as well as its transportation, use and maintenance, and concludes with the end-of-life operations. This last stage includes recycling of materials and, after adequate treatment, final disposal of waste. This paper summarizes the presentations, discussions, and recommendations of the NIST Workshop "Sustainable Manufacturing: Metrics, Standards, and Infrastructure" held at NIST, Gaithersburg, Maryland, USA, October 13th through October 15th, 2009. The paper is organized as follows: Section 2 provides an overview and objectives of the workshop, Section 3 provides summaries of the keynote presentations, Section 4 summarizes the technical session presentations, Section 5 summarizes breakout groups' recommendations and action items, and finally Section 6 provides a summary of the overall outcomes of the workshop.

2. Overview of the workshop

The primary objective of this workshop was to bring together experts and various stakeholders to identify and discuss measurement and standards' enablers that positively affect the social, economic, environmental, and technological aspects of designing sustainable production processes, products, and services.

The workshop consisted of technical sessions (which included three keynotes), breakout discussions, and industrial showcases that addressed important issues necessary for the production of sustainable systems.

The topics for the technical sessions included (subtopics are given as examples):

1. Develop general notion of sustainable manufacturing
   - Including indicators, indices, metrics for sustainability, sustainable manufacturing maturity model, macro level and micro level sustainability, the notion of triple bottom line, and corporate social responsibility.

2. Design of sustainable products, services, and manufacturing systems
   - Integrating environmental aspects into product design and development, design for process and product sustainability, product life cycle management and life cycle analysis, material science, advanced manufacturing technologies, nano-manufacturing, energy efficiency, conservation for production and use of products, reduce, reuse, and recycling, information infrastructure including advanced models and semantics for product and process, and manufacturing simulation.
3. Establish standards and industry best practices for sustainable systems
   - To include standards landscape for product, process representation, national and international standards and regulations for sustainability (e.g., ISO 14000, Restriction of Hazardous Substances (RoHS), Registration, Evaluation, Authorisation and Restriction of Chemical substances (REACH), and Waste Electrical and Electronic Equipment (WEEE)), risk analysis of policy instruments (cap and trade), regulations, and cost of compliance.

4. Develop next generation information and communication technologies (ICTs) for sustainable manufacturing
   - ICT for design, manufacturing, and supply chain optimization for sustainable manufacturing.
   - Large scale data modeling and semantic technologies for sustainable manufacturing
   - Tools, standards, and industry best practices for sustainable systems.
   - Interoperability among Product Life cycle Management (PLM) and Life cycle assessment (LCA) tools to support energy and material monitoring and saving.

3. Inaugural and Keynote Presentations

Howard Harary, Acting Director, Manufacturing Engineering Laboratory (MEL of NIST), chaired the inaugural session, where he stressed the importance of sustainable manufacturing and the role of metrics and standards. He also gave a brief overview of some of the research and standard activities of MEL, in particular in the area of sustainable manufacturing. Howard Harary requested the participants to focus their attention on business perspectives of sustainable manufacturing, regulations and their local and global impacts, various academic initiatives; and encouraged the participants to explore and leverage various government initiatives on sustainable manufacturing. Patrick Gallagher, Director, National Institute of Standards and Technology (NIST), in his inaugural address underscored NIST's commitment to realizing the Department of Commerce's high-priority performance goal in sustainable manufacturing. He emphasized that the goal of NIST is to help U.S. industry to be the leader in the development and manufacture of innovative, sustainable products and related services. Patrick Gallagher also gave a brief overview of several ongoing sustainability programs at NIST, which address other sustainability issues such as energy efficient buildings, waste reduction in the semiconductor industry, measurement techniques for accurately determining greenhouse gas content, and innovative materials research. Vijay Srinivasan, Chief, Manufacturing System Integration Division (MSID of NIST), outlined how business and research communities are viewing sustainability in general and in particular sustainable manufacturing. Synthesizing various surveys and studies, he underscored the level of commitments shown by senior level business executives in implementing sustainability programs in their enterprises. Vijay Srinivasan drew a parallel between sustainability efforts with the quality movement, as noted in this quote, "*We are in the sustainability movement where we were with the total quality management (TQM) nearly 30 years ago. It will be a long, but useful journey.*"

There were three keynote presentations, one each from industry, government, and non-government organizations.

The keynote speakers included Mary Saunders, Assistant Secretary Manufacturing and Services, International Trade Administration (ITA), Department of Commerce; Mark Cohen**,** Vice President for Research at Resources for the Future; and Bob Bechtold, CEO of HARBEC Plastics Inc.. Mary Saunders described recent developments in the Sustainable Manufacturing Initiative of the Manufacturing and Services (MAS), while Mark Cohen gave an overview on sustainability reporting and the Global Reporting Initiative (GRI). Bob Bechtold presented a case study of small and medium-sized enterprises (SMEs) and lessons learned from implementing sustainability practices.

4. Summary of Technical Presentations

4.1 Government Initiatives

The objective of this session was to get an overview of the sustainable manufacturing initiatives taken by the government, with some insights into ongoing work at various government organizations. Following Ms. Saunders keynote address, the other presenters in this session were George Hazelrigg from the National Science Foundation (NSF), Gordon Gillerman from the Standards Services Division (SSD of NIST), Ram Sriram from MSID (of NIST) and Kevin Watson from the National Aeronautics and Space Administration (NASA).

Hazelrigg, NSF, pointed out that NSF seeks to fund fundamental research in education, but sustainability has not been specifically identified as a funding area within NSF. At the current consumption and population growth rates, George estimates that our energy reserves (fossil, nuclear, and solar) will last another 1000 years. On the other hand, we will soon run out of air, water, food, and space. Manufacturing must use less water, less energy, less scarce and toxic materials, and produce less waste. He introduced the concept of "Energy Manufacturing," which considers energy as a manufactured commodity. Feedstocks, capital, and labor are inputs and energy is the output. George also talked about optimizing design for manufacturing. Knowing the type of facility that will be used for manufacturing at design time can help to optimize both the design and the manufacturing process. However, this calls for better modeling of the manufacturing processes, and better understanding of decision making under uncertainty. He noted that in the quest for a definition for sustainability, we must be mindful of Arrow's impossibility theorem. Hazelrigg identified that science and engineering can help to define the impact of manufacturing on the environment, estimate the consequences and present opportunities for change, and estimate their costs. Hazelrigg felt NIST could make crucial contributions in these areas.

Gordon, **NIST**, whose presentation was entitled "Standards Conformity and Assessment," opened by stating that delivery of services in a supply chain requires uniform understanding between the actors in the supply chain. We need standards for achieving this and NIST can contribute in this area. We also need quality standards and product performance standards in many areas, such as body armor covering[3], production management and supply chain. Gordon noted that globalization has turned standards into an international business, and NIST must play crucial roles in both policies and standards. Gordon suggested that we must look to industry/private consensus standards first, and government unique standards as the last resource. When the toy industry delivered unsafe goods to the retailers, Wal-Mart reacted by doing their own testing. However, it is very inefficient for retailers to test themselves. It is important for government organizations to take these initiatives forward by working closely with the industry. Gordon concluded by saying that green products need a lot of standards work, and expected NIST to deliver in this area.

Ram Sriram, NIST, gave an overview of the Sustainable and Life cycle Information-based Manufacturing (SLIM) program at NIST. Ram Sriram felt that our personal destiny is our choice, and the same can be said about sustainability. When talking about sustainability, Ram felt that we

[3] http://www.nist.gov/cgi-bin/view_pub.cgi?pub_id=33027

must talk in terms of the whole life cycle of the product. The three dimensions of a product life cycle are business, process, and product. The SLIM program focuses on the information technology aspects associated with these dimensions. The historical view of products has centered around geometry – today, we need to focus on other semantic aspects as well, including form, function, behavior and constraints. Some of the challenges addressed in the SLIM work are: 1) evolving STEP to be compliant with Object Management Group (OMG) and World Wide Web Consortium (W3C) standards; 2) a core product modeling framework that supports form, function, and features; 3) organization and harmonization of standards; 4) long term knowledge retention; 5) indicators for sustainable manufacturing and 6) simulation of manufacturing enterprises.

Kevin Watson, **NASA,** gave a presentation titled "NASA Manufacturing Supply Chain Sustainability Issues." A new executive order released a week before this workshop requires NASA to report scope 3 emissions[4], which include emissions from NASA's supply chain. Kevin pointed out that Department of Energy (DOE) has given guidance on the definition of quantitative indicators to determine a baseline and measure of progress towards goals. The indicators must be meaningful, additive and must have readily available data or use existing data. There must be an allocation of goals into the supply chain and integration of supply chain contributions to the achievement of these goals. Kevin mentioned that the way forward is in the identification of mechanisms for encouraging the prime contractors to accept the defined goals and to flow them down through their supply chain, find mechanisms for collaboration with contractors, and other government agencies, and provide assistance in achieving the defined goals. Kevin concluded by describing some technologies developed at NASA, including a rapid metal fabrication process that requires a minimum amount of machining and a green manufacturing technology that makes efficient use of feedstock and energy, while producing minimal waste.

4.2 Industry Perspectives

This session involved participation from industry leaders, focusing on the costs, benefits and challenges in incorporating sustainability in the industry. The objectives for this session were multifold: identify the major concerns in the industry regarding energy efficiency, waste etc.; get an insight into industry practices affecting sustainability factors such as environmental impact and social impact; gauge industry response to sustainability directives such as RoHS and REACH; and get industry feedback on regulatory directives and standards and the way forward. Following Bob Bechtold's keynote address (described earlier) for this session, presentations were given by participants from various industries, including the automotive industry (Ford, General Motors (GM)), aerospace industry (General Electric (GE) Aviation), high-tech industry (Lockheed), engineering consulting (Rockwell Automation), consumer goods industry (Procter

[4] GHG (green house gas) Protocol identifies three potential "scopes" for a corporate GHG inventory. Scope 1 encompasses a company's direct GHG emissions, whether from on-site energy production or other industrial activities. Scope 2 accounts for energy that is purchased from off-site (primarily electricity, but can also include energy like steam, compressed air). Scope 2 emissions physically occur at the facility where electricity is generated. Scope 3 is much broader and can include anything from employee commute, to "upstream" emissions embedded in products and processes, to "downstream" emissions associated with recycling, transporting and disposing of products. Scope 3 is an optional reporting category that allows for the treatment of all other indirect emissions. Scope 3 emissions are a consequence of the activities of the company, but occur from sources not owned or controlled by the company.

& Gamble (P&G)), office products (Xerox), process industry (URS Corporation) and home products (Masco Retail Cabinet Group).

The presentations from the industry participants covered sustainability initiatives taken by the respective companies, describing steps taken in reducing carbon emissions, improving energy efficiency, and reducing waste. Summaries of the individual presentations are described below. One important observation, acknowledged by all the participants, is that NIST and other standards bodies should play a central role in addressing these concerns.

Margaret Lindeman, Lockheed Martin (LM), presented an overview of LM's *Go Green*[5] program. The main drivers for this program were reducing business risk by reducing dependency on natural resources and managing future regulatory expectations, while supporting customer objectives on environmental impact reduction, and being a good corporate citizen. Lockheed Martin's objectives for 2012 are to reduce carbon emissions, waste to landfill, and water usage by 25 %. Internally developed survey tools are measuring LM's performance, but the company plans to migrate to SAP Carbon Impact[6]. LM's energy efficiency projects have already yielded savings of 37.8 million kWh and $3.3 million in cost avoidance, and the company has reduced carbon emissions by over 4,800 metric tons, resulting in savings of more than $500,000. LM saved 11 million kWh and $1.2 million in operating costs by consolidating 1,700 IT servers. By 2008, the company had reduced carbon emissions by 3 % (by energy management and lighting upgrade), waste to landfill by 9 % (partnering with a vendor to recycle waste, which means that less than one percent of the site's waste will be sent to landfills) and water consumption by 11 % (by repairing leaks, improving efficiency, recycling process water and innovative landscaping projects).

Korhan Sevenler, Xerox, in his presentation entitled "Environmental Printing and Compliance Management at Xerox" described a new printer developed at Xerox that uses cartridge-free solid ink to reduce waste by 90 %. Korhan Sevenler identified regulatory compliance pressure, such as RoHS and REACH, as the leading reason for companies to take action on material content restrictions. He pointed out that Xerox cannot sell their products in Europe without meeting regulations like REACH, and this requires coordination and oversight of their supply chain --- over 2000 suppliers --- to ensure compliance. Xerox uses InSight[7] software for compliance management. Korhan also noted that there is some confusion about the directives coming from European Union (EU) and other organizations, and that organization like NIST can play a significant role in coordinating and knowledge sharing.

Stephan Biller, General Motors (GM), talked about the energy challenges in automotive manufacturing. About 36 % of the energy consumption in manufacturing is in painting. Transmission assembly accounts for 19 %, engine 13 %, stamping of sheet metal 12 %, and body structure and general assembly 10 % each. Painting is therefore a good candidate for energy reduction. Stephan proposed real-time control, better process design, and better

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[5] Lockheed Martin's Go Green program: http://www.lockheedmartin.com/aboutus/energy_environment/going-green.html

[6] SAP CARBON IMPACT: Carbon Management Software to Measure & Offset Greenhouse Gas Emissions, http://www.sap.com/solutions/sustainability/offerings/carbon-impact/index.epx

[7] InSight Environmental Compliance: http://www.ptc.com/products/insight/environmental-compliance

equipment design as paths to energy savings. Part of the energy consumption in painting may be reduced if reentry time (for maintenance purposes) into the painting booth is reduced. GM found that the measured safe reentry time is much shorter than originally thought. To identify opportunities such as these, we need better data, better standards, and better measurement methods. Stephan observed that NIST could make valuable contributions in this area. He identified research opportunities in creating information models for energy decision-making, determining the level of carbon generated in the production of a specific vehicle configuration and methods to optimally allocate credits when considering developing remanufacturing supply chains.

Mary Burgoon, Rockwell Automation, gave a presentation entitled "Sustainable Production and Supporting Standards." Rockwell Automation is the leading global provider of industrial automation, power control and information solutions products which are used to control manufacturing processes. Mary observed that sustainability is a natural extension to Rockwell Automation's business goals of improving cost, quality, and productivity. The company's sustainability portfolio addresses not only energy and environmental concerns, but also workplace and product safety. Rockwell Automation's intelligent motor control portfolio (*PowerFlex*[8] and *IntelliCENTER*[9]) and software for continuous emissions monitoring (*Pavillion CEM*[10]) help address energy efficiency and environmental safety needs. The company also provides pre-engineered safety solutions and safety engineering services to address machine safety, process safety and worker protection. Mary pointed out that Rockwell Automation actively participates in standards activities for Smart Grid[11], energy management, environmental standards, and social responsibility standards.

Robert Crawford, Proctor & Gamble (P&G), provided an overview of the sustainability program at P&G. Robert noted that 75 % of their customers are interested in sustainability, but they are not willing to pay more for it. P&G's cost reduction strategies for their products include condensed detergent, slimmer diapers, packaging reduction etc. The company created a resource conservation measures system. On average, 96 % of all materials are converted to a finished product. P&G uses the EPA transport distribution system to minimize traffic transport.

Todd Rockstroh, General Electric (GE), reflected on GE Aviation's perspectives on sustainability. Todd described the Overall Equipment Efficiency (OEE)[12] as one affordable solution for measuring sustainability. This allows GE Aviation to find the most common and most expensive energy leaks. Intelligent manufacturing must use upstream information to reduce rework, scrap, and variation. Additive fabrication is a GE initiative that reduces raw material and machining required to make a part, and simplifying large components and combining multiple small components. Todd identified the main challenges for a regulated industry as the need for tools to assess carbon impact when changing manufacturing parameters, and tools to assess the risks and financial impacts of changing manufacturing processes. The value of information models cannot be realized without the capability to use them in real time, and identifying

[8] Allen-Bradley PowerFlex family of drives from Rockwell Automation, http://www.ab.com/drives/
[9] IntelliCENTER Software from Allen-Bradley, http://www.ab.com/mvb/intellicenter.html
[10] Pavilion8 Software CEM: Pavilion's Predictive Emissions Monitoring System, http://www.pavtech.com/index.php?option=com_content&task=view&id=200&Itemid=117
[11] Smart Grid: http://www.nist.gov/smartgrid/
[12] OEE: An effective benchmarking tool in making sound decisions, http://wcm.nu/OEE/oee.html

measurement touch points. Todd recommended that NIST should work with the industry and other partners in developing these information models.

Kathi Futornick, URS Corporation, focused on industrial regulations and standards, in particular metrics for sustainable performance. Kathi Futornick noted that environmental regulations should go beyond the EU directives and should be the major driver for sustainable and global environmental compliance programs. The supply chain is the weakest link for compliance management. Most supply chain partners do not see a linkage between the environment and their operations, and do not use metric to measure sustainability. The reason cited by suppliers is that their contract does not mention sustainability. As an approach to compliance, Kathi suggested self-declaration by manufacturers, which can be enforced by market surveillance. URS Corporation looks at declarations, performs destructive and non-destructive tests, and develops fishbone diagrams showing what feeds into product quality. Kathi described Wal-Mart's supported Sustainable Product Index (SPI)[13] program, which has three phases: the first phase addresses its supply chain (*15 Questions for Suppliers*); the second phase is life cycle assessment, which involves a comprehensive assessment of raw material production, manufacturing, distribution, use, and disposal including all transportation and environmental impacts; and in the third phase the SPI is displayed on products on the shelf for consumers to see and use in their buying decisions. Kathi also listed some other voluntary programs that address vendor/supplier requirements and related issues. Finally, Kathi stressed the need for a systems approach to sustainability, and widespread industry alignment with regulations as a catalyst for achieving sustainability.

Gahl Berkooz, Ford Motor Company, spoke on the opportunities for information standards in sustainability and compliance. Gahl began by listing some of Ford's achievements: Ford Fusion Hybrid, rated best mid-size hybrid sedan in America; and Ford Fiesta ECOnetic, rated UK's greenest family car. The Ford Rouge Complex[14] in Michigan has one of the world's largest green roofs. Gahl identified the main information challenges to sustainability, namely, the cost of regulatory compliance and reporting, and the cost of assessment of the environmental footprint of products in transit. Gahl observed that standards could play a significant role in reducing these costs. He also noted that regulations were reactive in the past (pollution control), then became anticipatory (pollution prevention), and are moving towards high integration and transparency (eco-efficiency, environmental cost accounting systems). The challenge for Information Technology (IT) is to develop proactive frameworks that are flexible, decrease compliance costs, and help assess risks. Reactive IT frameworks are costly, have redundant information flow, and new systems must be built for new regulations. Gahl felt that standards organizations could help industries in environmental reporting by mapping the regulations to available standards. Another significant problem is to build a bridge between information standards and legacy data, to avoid duplication and improve risk assessment. Gahl recommended that NIST play a significant role in the development of these standards.

The final presentation of the session was by **Denise Van Valkenburg, Masco Retail Cabinet Group (MRCG)**, which was entitled "Integrating Sustainability into Manufacturing Systems." Denise pointed out that we need to get past the idea of using regulations as a catalyst. She

[13] Wal-Mart's Sustainability Index: http://walmartstores.com/Sustainability/9292.aspx
[14] The Ford Rouge Complex: http://www.thehenryford.org/rouge/index.aspx

described “Design for the Environment” (DfE) as a method of identifying major environmental concerns regarding product design, manufacturing process, direct productive materials, and indirect processing materials. The main drivers for this are environmental regulations, green product initiatives, and customer demand. DfE ensures continuous environmental improvement by a process of review of existing designs and environmental audits and improvement goals. The MRCG Manufacturing Management Operating System (MRCG MMOS) is a standardized process designed to align goals, drive performance, measure compliance, and stimulate continuous improvement from the shop floor up to and including the executive scorecard. The primary categories it addresses are health and safety, environment, quality, performance, and schedule attainment. MRCG MMOS includes total employee involvement; uses structured reporting and integrates environmental metric scorecards. Lean Information Control System (LINCS)[15], a web based software tool, is used to support it, and the resulting improvements have led to substantial reductions in waste and earned awards for MRCG.

4.2.1 Summary of the Industry Perspectives

While each of the above presentations covered the activities of a particular company, many common issues were raised that swept across industrial sectors. The most important observations are summarized below.

Need for improved standards and regulations: Current sustainability related standards and directives are evolving, and more work is needed to produce mature standards. Much of this work is related to improving the science behind the standards, and balancing the scientific and metric aspects to the associated business aspects. The business impact of such a standard must be carefully addressed. For instance, Korhan Sevenler from Xerox noted that while RoHS mentions six substances, REACH covers thousands. Mary Burgoon from Rockwell Automation stressed the importance of machine and electrical safety, and maintaining worker protection and productivity. The participants agreed that these directives must be carefully formulated to ensure compliance and be of value to the industry. Stephan Biller from General Motors argued for better standards that can drive the design and implementation of manufacturing processes. For example, well-developed standards and better measurement technologies could lead to reduced down times during production. In addition, Denise Van Valkenburg from Masco Retail Cabinet Group and Korhan Sevenler claimed that regulations are necessary to drive the industry towards sustainable practices. NIST could be one of the primary institutions that could play a leading role in developing and championing these standards.

Guidelines for regulations and reporting: While there was a feeling that the regulations themselves are not fully developed, there is an urgent need for guidelines on reporting and information management related to compliance. Korhan Sevenler highlighted the need for coordination and knowledge sharing to cope with the different directives coming from different organizations. Todd Rockstroh emphasized the importance of being able to use information models in real time to assess risks, while Gahl Berkooz added that we need proactive IT frameworks that are flexible and will result in reduced compliance costs. Kathi Futornick illustrated some examples such as Wal-Mart’s Sustainable Product Index. It was observed that

[15] Lean Information Control System, LINCS , http://www.usccg.com/tech/lincs.php

NIST and other government agencies should play a significant role in taking these initiatives forward, while ensuring that there is a fair and level playing field for all businesses.

Compliance management in the supply chain: One of the recurring themes in the presentations was compliance management in the supply chain. Korhan Sevenler noted that American companies face supply chain disruptions in Europe due to REACH restrictions. Kathi Futornick called the supply chain the "weakest link," noting that most supply chain partners do not see a connection between environment and sustainability and their operations. There was a consensus on the challenge of managing the supply chain, and the need for standards and practices directly addressing compliance in the supply chain. Sevenler suggested that NIST could contribute towards the development of such a standard.

4.3 University Research

The university session provided workshop participants an opportunity to articulate various research issues in sustainable manufacturing. Most speakers agreed that sustainable manufacturing issues are challenging, and emphasized the necessity of a system approach that can synthesize the triple bottom line, life cycle views for metrics, and information systems. Since many of the speakers in this session have touched on breadth of research issues, we provide the summary according to the broad research topics.

System approaches: Bert Bras, I.S. Jawahir, and John Sutherland collectively pointed out that closed-loop material flow should be considered in making a system more sustainable. A closed-loop material flow could be expressed as a process consisting of extracting materials from nature, manufacturing, supply chain, and through the 3Rs (reuse, recover, and recycle processes). Closed loop material flow encourages recovery, reuse, and recycling of materials. I.S. Jawahir expanded the closed-loop material flow to 6Rs, viz. redesign, reduce, remanufacture, reuse, recover, and recycle processes.

Bert Bras also discussed the emphasis that industry places on various aspects of the closed loop product life cycle. The initial focus is on improving the manufacturing process. After manufacturing processes are optimized, the focus goes back to the design stage to improve product design. Then, industry efforts on sustainable manufacturing focus on material sourcing (extraction), supply chain, and eventually the 3Rs. The following issues were presented in the workshop.

Manufacturing process analysis: John Sutherland shared lessons from his analysis of a machining process. He mentioned that a characterization of a manufacturing process is required to measure the environmental impact of the process. For example, different processing conditions and alloy types affect the environmental impact of a machining process. In addition, he recommended that not only energy consumption but also air quality during production must be investigated for the health and safety of workers.

Sustainable Design: Bert Bras, Ramani Karthik, and John Sutherland reiterated that sustainable design is critical because of its downstream impact on the environment. Karthik Ramani proposed how engineers can use an LCA tool in the conceptual design phase. Engineers want to estimate the environmental impacts of their conceptual designs. However, most previous tools for sustainable design failed to estimate the environmental impacts of a conceptual design because conceptual design data are neither complete nor detailed. Therefore, he proposed a way to estimate the environmental impacts of a conceptual design. Karthik Ramani used the environmental impact data of existing products. He analyzed the environmental impacts of existing products for their functions. Then, he estimated the environmental impacts of a conceptual design using the function-impact matrix. The function-impact matrix provides estimated impacts of functions and enables engineers to distribute the impacts to components of a conceptual design. His research resulted in identifying up to 70 % of conceptual design accounts for 70 % of the environmental impacts. Bert Bras and John Sutherland pointed out that sustainable design requires creativity and a service-oriented approach. Previous design approaches focused on redesign of components to use less material. However, the service-oriented approach, which involves selling services (e.g., printing services) rather than actual products, can be more sustainable than the previous approaches. Bert Bras showed the service-oriented approach example in the camera industry. He used an LCA example to show that providing services (printing services in wholesale) instead of products (PC printers in houses) can be better.

Supply chain analysis: John Sutherland pointed out that the growing priority of sustainability would have an impact on suppliers, facility location, size, and distribution. It requires determining the environmental impacts of a product by summing impacts of its components and materials across the supply chain. Then he raised issues such as modeling supply chain processes, information systems for data collection, interoperability, and the need for a compliance infrastructure for metrics, standards, and regulations.

Kincho Law addressed various issues about supply chain process modeling and implementation. He recommended an open standards approach. He proposed GreenSCOR, which is a framework for modeling supplying chain processes. In addition to performance metrics included in the Supply Chain Operations Reference (SCOR) framework[16], the GreenSCOR includes additional metrics for evaluating the environmental footprint. He also suggested using open standards such as Business Process Modeling Notation (BPMN)[17], Business Process Execution Language (BPEL)[18], Web Service Definition Language (WSDL)[19], and Simple Object Access Protocol (SOAP)[20] for supply chain process models and web services. Kincho demonstrated a prototype system -- called “SC Collaborator.” The system provides user-interfaces to collect the environmental footprint of components from participants across the supply chain. Then, the system aggregates and calculates those data and reports the total environmental footprint of a product.

Reuse, Recovery, and Recycle: Reuse, recovery, and recycle processes must get more attention

[16] Supply Chain Council, SCOR Frameworks, https://www.supply-chain.org, 2009
[17] Object Management Group, Business Process Model and Notation (BPMN), http://www.omg.org/spec/BPML/2.0, 2009
[18] Organization for the Advancement of Structured Information Standards, Web services business process execution language version 2.0 primer, http://docs.oasis-open.org/wsbpel/2.0/primer/wsbpel-v2.0-primer.pdf, May 2007.
[19] World Wide Web Consortium, Web services description language (WSDL) version 2.0, http://www.w3.org/TR/wsdl20-primer, June 2007
[20] World Wide Web Consortium, SOAP version 1.2 part1: messaging framework, second edition, W3C recommendation, April 2007.

from researchers because these have considerable impacts on sustainability. According to Bert Bras and John Sutherland, recycling materials requires much less energy than refining raw materials. For example, recycling 1 metric ton of aluminum requires 20 kW of power, while its refining process requires 14,000~15,000 kW of power. Thus, Bert Bras and John Sutherland emphasized that de-materialization should be a very high priority from an energy point of view.

Metrics: Research on sustainability metrics attracted considerable attention in the workshop. Most participants showed interest in the semantics of metrics[21], computation of metrics, and use of metrics for decision-making. Speakers in the university session addressed several of these issues.

Sustainability metrics described by speakers reflect the triple bottom line. Hong Zhang showed a list of ISO standards related to the triple bottom line, and briefly explained about the United Nations Commission on Sustainable Development Framework (CSD)[22]." The framework provides a classification of sustainability metrics or indicators. It classifies indicators into four sustainability aspects such as social, environment, economic, and institutional aspects and classifies indicators further into sub-categories for each aspect.

I.S. Jawahir suggested that sustainability indicators should be classified according to the levels of measured objects such as product, process, enterprise, and supply chain. He applied the multi-level approach in classifying indicators developed by the Organization for Economic Co-operation and Development (OECD).

Sustainability index calculation methods and using metrics for decision support: I.S. Jawahir described a methodology for calculating a sustainability index. He used the weighted sum of scores between 0-10 for each influencing metrics. If a metric is measurable, and the minimum and the maximum of the metric are known, the metric can be converted into a score between 0-10. If a metric is not measurable, it can be scored between 0-10 based on designers' experience. Although sustainability metrics/indices for different materials/products/scenarios can be calculated, it may not be clear that one is better than other. For example, material 'A' may be good for the environment, but it may not be good when assessing the social/economic impacts. Meanwhile, material 'B' may not be good for the environment, but it may be good for assessing the social/economic impacts. However, there is neither a guideline nor an evaluation method to make a trade-off between environmental impacts and social/economic impacts. David Ervin and Hong Zhang addressed this issue in the workshop. David Ervin proposed a monetized approach to calculate sustainability indices. The approach monetizes all metrics of the triple bottom line using the genuine savings concept, so that it resolves the summation difficulty of different metrics and allows substitution between natural capital and other forms. The Genuine Metrics is based on Genuine Savings[23], which focuses on analyzing the economic benefits and costs associated with development activities. Genuine Metrics is essentially a method for combining

[21] Metrics and indicators are used interchangeably here.
[22] The United Nations Commission on Sustainable Development (CSD) was established by the UN General Assembly in December 1992 to ensure effective follow-up of United Nations Conference on Environment and Development (UNCED), also known as the Earth Summit. http://www.un.org/esa/dsd/index.shtml
[23] J.Ram Pillarisetti, The World Bank's 'genuine savings' measure and sustainability, Ecological Economics, Volume 55, Issue 4, 1 December 2005, Pages 599-609

financial and environmental data.

Hong Zhang pointed out that current LCA techniques have limitations for making trade-offs between environmental protection and both social and economic concerns in the product life cycle. Since LCA traditionally does not take into account social and economic impacts, Hong Zhang proposed social and economic indicators for LCA. He presented a technique based on the principal component analysis (PCA) technique to aggregate sustainability indicators on a variety of scales.

Information systems: Most issues for sustainability information systems are coupled to the aforementioned issues. Typical information system issues are data/service interoperability and process/information modeling issues across the supply chain. Kincho Law proposed an open standards approach for developing an information system, which can collect data across the supply chain and report environmental footprints. He used the EU LCA dataset[24] to calculate footprints because it is open to the public and free.

Bert Bras shared his experiences about sustainability software development for manufacturing companies. He presented an extension to the activity-based costing (ABC) approach to assess environmental impacts, but he found that it was difficult to apply the ABC approach to the manufacturing company he worked with because the company had incompatible financial systems.

4.4 NGO Research

The Non-Government Organizations (NGO) Research section had participation from various NGOs and Standards Developing Organizations (SDOs), and industry consortia, focusing on various standards development efforts, harmonization of standards, and sustainability reporting mechanisms and standards. The speakers were asked to give an update on various standards development efforts and progress in implementing these standards in terms of accounting and reporting, verification and validation, and product labeling. Currently there are three competing standards related to sustainability:

1. PAS 2050[25], which is a specification for the assessment of the life cycle greenhouse gas emissions of goods and services.
2. ISO 14000 series of standards, which are developed under ISO TC 207, apply to standardization in the field of environmental management systems and tools in support of sustainable development.
3. GHG Protocol-Product and Supply Chain Standard developed jointly by World Resources Institute (WRI) and World Business Council for Sustainable Development (WBCSD) to support the public reporting of product level GHG emission inventories for all products and services in all market sectors.

The above standards need to be harmonized so that industry can implement them in an effective manner.

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[24] European commission's joint research centre, ELCD core database version II, http://lca.jrc.ec.europa.eu/lcainfohub/datasetArea.vm, 2009.
[25] The British Standards Institution, http://shop.bsigroup.com/en/Browse-by-Sector/Energy--Utilities/PAS-2050/

The session began with a keynote address by Mark Cohen**,** Vice President for Research, Resources for the Future, whose presentation was summarized in Section 3. This was followed by presentations by participants from various SDOs, NGOs, and industry consortia, including the American National Standards Institute (ANSI), American Society for Testing and Materials (ASTM), World Resource Institute (WRI), National Center for Manufacturing Sciences (NCMS), National Council For Advanced Manufacturing (NACFAM), and Cadmus Group. The presentations covered standards development efforts, an overview of US standards development process, sustainability metrics, and progress in implementing these standards in terms of accounting and reporting, verification and validation, and product labeling.

Pankaj Bhatia, **World Resources Institute (WRI),** Director of GHG Protocol Initiative, gave an update on the product accounting and reporting standard and gave a brief overview on a new initiative called Greenhouse Gas Protocol Product and Supply Chain Initiative. The two published standards under this initiative are: 1) A Corporate Accounting and Reporting Standard (Corporate Standard), and 2) The GHG Protocol for Project Accounting. (These can be downloaded from the following URL: http://www.ghgprotocol.org/standards.) He also mentioned they are developing two new standards, namely, Scope 3 (Corporate Value Chain) Accounting and Reporting Standard and the Product Life Cycle Accounting and Reporting Standard (product carbon foot printing). The main objectives of the Product Life Cycle Accounting and Reporting Standard are to:

1. Support the public reporting of product level GHG emission inventories for all products and services in all market sectors
2. Support other uses of product GHG information, e.g., internal product reduction decisions, and tracking of emissions for internal purposes
3. Help users of the standard reduce emissions by making informed decisions about the products they manufacture, buy, use, and sell.

Pankaj also stressed that there is a growing demand to compare similar products based on their life cycle GHG emissions. However, there are many technical challenges in ensuring that such comparisons are valid. To do so, there is a need for methodological consistency at the product category rules (PCR) level. PCRs provide a mechanism for agreeing on specific rules in relationship to individual product categories. PCRs are established under ISO 14025:2006[26] with the aim of improving comparability. The environmental performance of products differs significantly according to the product categories (where a product category is defined as a group of products, which can fulfill equivalent user needs). Hence, it is critical to select a set of appropriate indicators and calculation rules. To achieve this objective, Product Category Rules (PCR), formerly called Product Specific Requirements (PSR), corresponding to the general EPD program requirements are defined. According to ISO 14025, PCR are a set of specific rules, requirements, and guidelines for developing Type III environmental declarations for one or more product categories. Three different types of environmental labels and declarations are currently in use. They include: Type I environmental labeling, Type II self-declared environmental claims, and Type III environmental declaration.

Further research work in product carbon foot printing is currently being undertaken. This

[26] http://www.iso.org/iso/iso_catalogue/catalogue_tc/catalogue_detail.htm?csnumber=38131

underscores the widespread recognition of the limitations of the previous international standards and the need for consistency in the methods used. He also mentioned that the WRI/WBCSD (World Business Council for Sustainable Development) announced in July 2008 that they would be collaborating on a product carbon foot-printing project, while the International Standards Organization voted in November 2008 to proceed with development of a new international standard on product carbon foot-printing (ISO 14067:2008).

Manish Mehta, **National Center for Manufacturing Sciences (NCMS),** Executive Director, Industry Forums & Technologies Research Corporation, gave an overview of collaborative initiatives for sustainable products manufacturing at NCMS. Specifically, he highlighted the Sustainable Product Initiative (SPI), a six-year EPA (Environmental Protection Agency) sponsored program (2004-2010) for developing "best practices," design criteria, analytical tools, manufacturing capabilities and/or recovery techniques for future products, resulting in an enhanced level of environmental acceptability and sustainability than products that are currently available. The main target sectors are automotive, office furniture, and textiles. As part of this initiative, NCMS has developed a Sustainable Product Standards Guide, a collaboratively developed "How-to" document addressing multi-attribute standards development processes and pitfalls. NCMS has engaged leading organizations pursuing standards-related activities to confirm relevance and differentiation of the NCMS-led effort. NCMS is planning to release an advanced "draft" Guide by March 2010. A Wiki has been established to solicit broader input. (See http://spi.ncms.org/standards for details.) Manish also described some of the Life Cycle Assessment (LCA) projects at NCMS and showed details about Life Cycle Analysis of Volatile Organic Compounds (VOCs) in Paints & Coatings, called Coatings Counselor 2.0 LCA.

Gary Kushnier, **American National Standards Institute (ANSI),** Vice President of International Policy, gave an overview of the U.S. approach to standards and conformance, leading toward the goal of one standard, one test, one global acceptance and used the following notation (1:1:1) to emphasize this point. He pointed out that the main difference between the U.S. approach to standardization and that followed in other nations is that the U.S. uses the bottom-up approach where users drive standards and conformance activities. Whereas most nations follow a top-down approach, in which a centralized body drives standards and conformance activities. He also mentioned that the U.S. conformity assessment system, much like the standards system, evolved in a decentralized manner. Gary noted that the standards are just good ideas unless products, processes, systems, and personnel conform to them. Conformity assessment activities are not centrally organized and the approaches vary among sectors. He also gave a very brief overview of ANSI initiatives related to sustainability.

James D. Thayer, Cadmus Group, Senior Associate, and Professor, Portland State University, presented an idea of genuine metrics based on genuine savings. Genuine savings uses a firm's Property, Plant & Equipment (PP&E) as the baseline for its current sustainable base. Sustainability is calculated by adjusting this base for investments in, or depletion of, social capital and natural capital (resources). To translate the genuine savings model into an analytical framework for use at a corporate or operating level, the metrics are linked to the GRI sustainability indices. The last step adjusts the PP&E upwards and downwards by the appreciation and depreciation costs to find the net impact of sustainability activities. He explained the benefits of using genuine metrics.

Jeffrey Mittelstadt, **National Council for Advanced Manufacturing (NACFAM),** Vice President, Sustainable Manufacturing, gave an overview of NACFAM's Sustainability Framework Model. The main idea of this model is to develop and provide modeling for business decision-making with respect to sustainability. The model is based on existing financial and environmental metrics and is continuously enhanced through project applications. He also mentioned that NACFAM has established a Sustainable Manufacturing Council to advance U.S. manufacturers toward sustainable manufacturing.

Stephen Mawn, American Society for Testing and Materials (ASTM) International E60 Committee Staff Manager, gave an overview of ASTM and the current activities of E60[27]. Many ASTM International committees address sustainability, namely, infrastructure/built environment, water, agriculture, energy, products, waste, materials, and toxics. ASTM Committee E60 on sustainability was formed in 2008 and has more than 500 members. The technical subcommittees include the following: E60.01-Buildings and Construction, E60.02-Hospitality, and E60.80-General Sustainability Standards. The administrative subcommittee consists of the following E60.90-Executive, E60.91-Strategic Planning, and E60.95 Student Liaison and Affairs.

The E60 committee has so far published ten standards. Examples of these include ASTM E2432-Standard Guide for General Principles of Sustainability Relative to Buildings, and E2114-Terminology for Sustainability Relative to the Performance of Buildings Draft Standards. Stephen also mentioned that there are many sustainability standards under development: nine draft standards for sustainability in industry, and six draft standards related to sustainability in infrastructure/buildings are under preparation.

4.5 Software Solutions

The Software Solutions session predominantly focused on the need for tool support for sustainable manufacturing, in particular currently available tool support, and the standards compliance of the software applications. Companies are becoming increasingly interested in adhering to standards/directives such as RoHS and WEEE to compete globally. This calls for a systematic approach towards enabling these and other international standards at the institutional level as well as at the product level. Currently, there are several initiatives by individual software developers working closely with CAD companies to develop software support for environmental impact assessment of products, processes, and services. The software tools not only help companies assess the impacts of their products but also help them to determine if a product is compliant to a particular standard or not.

John Fox, **Parametric Technology Corporation (PTC)**, [28] Director, Product and Market Strategy, spoke on "Software Tools and Information Exchange Standards." He explained the importance of complying with sustainability-related product standards that will enable companies to be competitive in the global markets. He also explained how software could help companies assess the compliance of products by analyzing the life cycle of products, and all the components that go inside the product. John Fox described PTC's 'Insight'[29] software, which

[27] http://www.astm.org/COMMIT/COMMITTEE/E60.htm
[28] http://www.ptc.com/
[29] http://www.ptc.com/appserver/wcms/events/series.jsp?&im_dbkey=89520

could help designers assess whether a particular product is compliant to a certain standard or not. The software can process various kinds of data forms to create a database from suppliers, material database and legacy databases.

Michael J. Zepp, **Dassault Systemes**[30]**,** Director, Global Market Development Environmental Compliance and Sustainability, gave a presentation entitled "Innovation for Eco-Sustainability." He indicated that sustainable strategies create new usages and buying criteria for products and services. He also spoke about the importance of sustainable design using LCA and he expressed that software could be used to assess environmental impact and help designers design sustainable products. The importance of regulatory compliance and designing products for those compliant to various sustainability regulations could help us achieve eco- sustainability.

Laurie Jansen, Siemens[31], focused on Siemens strategy for incorporating sustainability in Siemens' PLM systems. She pointed out that developing sustainable products and processes require assessing the products to indicators that fall under environmental, social, and economical factors. Laurie called for an integrated approach towards LCA. According to her, sustainability could be achieved through the following tools and techniques: plan for sustainability, design for sustainability, practice sustainable manufacture, provide sustainable services, examine end of life, governance, compliance, and reporting.

Elena Arvanitis, **Siemens**, ended the session with her talk entitled "Sustainable Product Design and Manufacturing at Siemens: Sustainability Metrics and Environmentally Compatible Product Design." (Although her talk should have been a part of the industry session, it was included here due to scheduling constraints.) Sustainability is commonly measured as performance along a *triple bottom line*: environmental, social, and economical. Elena spoke about environmental performance and internal reporting, corporate responsibility, a corporate environmental protection program, and product-related environmental protection. Using examples, she explained how, by analyzing the life cycle of products, we could save energy and resources during product use and manufacturing.

5. Breakout Sessions

The breakout sessions consisted of two groups:

1. *Critical factors driving sustainable manufacturing:* The themes discussed in this group were business case for sustainability, promoting eco-innovation, standards and metrics, tool support, promoting reduced energy consumption, and positioning of standards.
2. *Decision support system for sustainable manufacturing:* The themes discussed in this group were standards harmonization, science of sustainability, greening the supply chain, data availability, and needs.

The participants generated recommendations or conclusions by selecting the best ideas or combining ideas for the "top attributes" identified. The group covered as many of the "top attributes" as possible.

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[30] http://www.3ds.com/
[31] http://www.usa.siemens.com/entry/en/

Group 1: Critical factors driving sustainable manufacturing

Group 1 took up the following set of key issues and subtopics for further elaboration, starting with this set and identifying the most common themes.

1. *Business:* how do the following diverse factors affect the business case: compliance, economic models, profit, case studies, and new sustainable products?
2. *Eco-innovation:* How to promote eco-innovation?
3. *Metrics:* How to develop metrics based on solid models, cases, and good data for model validation?
4. *Tools:* What are the gaps and problems with a methodology such as LCA? What is the business case for tools?
5. *Energy:* How to reduce energy consumption for sustainable growth?
6. *Standards:* How should standards be posed so that the positive incentive side drives them?

Group 2: Decision support system for sustainable manufacturing

Group 2 considered the following areas: Alignment of sustainability initiatives between US/EU/World, at local, state, and federal levels; sustainability product labeling and grading; standards, metrics, indicators, and standards' landscape for the enterprise; greening the supply chain; information modeling, semantic technologies, tools to support a systems approach; data availability and needs; education and outreach; cost of compliance and reporting; mathematical models and science of sustainability; and making a business case for sustainability. In the final deliberations, Group 2 focused on the following themes: 1. Harmonization of standards, 2. Mathematical models and science of sustainability, 3. Greening the supply chain, and 4. Data availability and needs. The NIST workshop report[32] provides a detailed description of the breakout sessions.

6. Concluding Remarks

The primary objective of the workshop was to bring together experts and various stakeholders to identify and discuss measurement and standards enablers that positively affect the social, economic, environmental, and technological aspects of designing sustainable production processes and products. The workshop was well attended with thirty presentations organized into five sessions: 1) Government Initiatives; 2) Industry Perspectives; 3) University Research; 4) Non-Government Organizations (NGOs) research; and 5) Solution Providers' Views.

The workshop participants identified several challenges faced by the manufacturing industry in its pursuit of sustainability goals and provided a set of key recommendations. The major challenges identified were as follows:

1. Industry is unable to measure economic, social, and environmental consequences of their activities and products accurately during the entire life cycle and across their supply chain. One of the main reasons for this is the lack of data traceable to a neutral organization. Even if the data were available, industry is finding it difficult to aggregate and disaggregate data to compute sustainability metrics.

[32] Sustainable Manufacturing: Metrics, Standards, and Infrastructure: Workshop report, Sudarsan Rachuri, Ram D. Sriram, Anantha Narayanan, Prabir Sarkar, Jae Hyun Lee, Kevin W. Lyons, and Sharon J. Kemmerer, NIST IR 7683, 2010

2. Full life cycle analysis or assessment of products requires new methods to analyze, integrate, and aggregate information across hierarchical levels, organizational entities, and supply chain participants.
3. Industry lacks neutral and trusted standards and programs to demonstrate, deploy, and accredit new sustainable manufacturing practices, guidelines, and methods.
4. There are too many metrics; they need consolidation and harmonization. Also, they need to be 'monetized' as appropriate.
5. Regulations need to be supported by industry standards (e.g., RoHS and IPC-1752). These regulations and standards should be harmonized.
6. Information standards are necessary to enable interoperability among engineering tools, business enterprise tools and Life Cycle Assessment tools for an integrated systems approach.

Key recommendations from the workshop participants follow, in no particular order.

Metrics (or indicators):

- Pursue a multi-level approach for metrics, with simple metrics at the highest level.
- Consolidate and harmonize the diverse set of existing metrics.
- Monetize metrics as appropriate.

Standards:

- Support regulations (e.g., RoHS) with industry standards (such as IPC-1752).
- Develop a strategy for the harmonization of many standards and directives that currently exist for sustainability.
- Create brand values for sustainability standards and maintain the brand values.

Infrastructure:

- Create a software infrastructure for gathering, analyzing, exchanging, and aggregating information for sustainability, including support for global data repositories.
- Develop a simple and transparent methodology for life cycle assessment calculation.
- Develop a science of sustainability, including open source models that are generic, extensible, verifiable, and easy to build and share.

Best Practices:

- Create a new business model for companies to apply the methodology developed for LCA voluntarily, which maximizes profits while minimizing costs.
- Develop best practices for eco-innovation, i.e., design of products and processes that are sustainable or contribute to sustainable development.
- Create eco-labeling for manufacturing processes and machines.
- Develop sustainability reporting standards for suppliers, and provide education and training to suppliers in simple terms, stressing the importance of compliance.
- Develop traceable life cycle inventory data to enable life cycle analysis of products, processes, and services and to enable verification and validation of life cycle impact measurements and benchmarking.