NISTIR 7975

Sustainable Manufacturing Program Workshop Report

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U.S. Department of Commerce
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EXECUTIVE SUMMARY

The NIST Sustainable Manufacturing Program held a workshop on November 13-14, 2012, at NIST in Gaithersburg, MD. Dr. Shyam Sunder, Director of NIST's Engineering Laboratory, initiated the workshop proceedings. In his opening remarks, Dr. Sunder explained the critical role of manufacturing for U.S economy and stressed the measurement science need for resource efficiency in manufacturing.

The main purpose of the meeting was to present the Sustainable Manufacturing Program plan and structure to the research community, as well as to provide the opportunity for the team to become acquainted with each other's contributions and better coordinate research and developmental efforts. The research team consists of NIST research staff working in the Sustainable Manufacturing program and external research partners. Between 40-50 experts attended, brainstormed, and identified pertinent research objectives that need immediate attention to achieve the Sustainable Manufacturing Program's research goals.

Dr. Sudarsan Rachuri explained the two thrusts of the Sustainable Manufacturing Program of the program, namely:

1. Methodologies for Characterizing Sustainable Processes and Resources
2. Integration Infrastructure for Sustainable Manufacturing

The remainder of the workshop addressed the following fundamental questions:

- To assess sustainable manufacturing what parameters should be measured to compute resource efficiency in terms of energy, material, and water?
- What are the key factors that contribute to uncertainty in sustainable manufacturing, how can these be prioritized, and what measurement techniques can be applied?
- How would a material model that supports sustainability decisions be formulated?
- How can sustainability data for a manufactured part or assembly be aggregated to enable sustainability analysis?
- What are the information modeling concepts that are unique to sustainability characterization and optimization?
- What are the characteristics of an effective manufacturing-focused sustainability assessment methodology?
- What are requirements and challenges for a shared research testbed and what types of things could be tested there?

Material information modeling was a key focus of the workshop. The participants debated whether effective capture of all relevant sustainability information would require the material information models be rooted in description and classification of unit manufacturing processes. The real challenge in developing a material information model, which is sufficiently flexible for capturing every unit manufacturing process, lies in the data structures and ontologies used in the overall system architecture. Further, the lack of existing measurement science and standards, including a lack of consistent information representation for unit manufacturing processes, are two problems that some researchers addressed as key concerns. Another element discussed was the depth of coverage in modeling sustainability information.

The main outcomes of the workshop were:

1. A clear path forward for each of the program teams in regards to the overall objectives and collaborative work.
2. Increased interactions between NIST team members and external stakeholders.
3. Better understanding of the team effort involved in realizing the program objectives.

The main recommendations from the workshop include:

- *Integrated Information Model:*
    - Develop a unified and integrated information model for product, assembly, materials, and processes
    - Develop a formal language for process representation to enable process aggregation
- *Sustainability Characterization and Optimization:*
    - Characterize unit manufacturing processes
    - Develop a taxonomy for processes and standard definitions for basic processes
    - Leverage work of other groups who have created such taxonomies
    - Develop an analytical framework for process simulation and optimization
- *Sustainability Assessment Methodologies:*
    - Develop a measurement science-based methodology[1] to enable analysis, allocation, and synthesis of the energy and material consumption at the factory level for gate-to-gate[2] lifecycle impact assessment
    - Develop a use case that can be used to showcase different aspects of sustainable manufacturing
    - Develop measurement science for product category rules (PCRs) to enable lifecycle assessment for product
- *Validation of the Information Models Using a Shared Research Testbed*
    - Develop a repository of models, methods, and test cases for research collaboration
    - Demonstrate integration and implementation of the three core information models for product, material, and process coherently and show how to retrieve the information required for sustainability assessment at any stage of the product lifecycle
    - Showcase the usability of the integrated information model for some benchmarking problem(s)

The remainder of the report is organized as follows: Section 1 describes the workshop goals and objectives including a description of the fundamental questions to be

[1] Methodology is defined as a collection of related processes, methods, and tools.

[2] Gate-to-gate is a partial analysis looking at only one value-added process in the entire production chain. Gate-to-gate modules may also later be linked in their appropriate production chain to form a complete cradle-to-gate evaluation.

addressed. Section 2 summarizes the discussions from the workshop. Section 3 provides a technology roadmap for sustainable manufacturing and the workshop recommendations. The Appendices contains working material from the workshop or by participants after the workshop as input to this report.

At the time of writing this report the Sustainable Manufacturing Program has evolved into a new program called Performance of Smart Manufacturing System (PSMS). The objective of the PSMS program is to deliver measurement science, standards and protocols, and tools needed to predict, assess, optimize, and control the performance of smart manufacturing systems. We will develop and deploy advances in cyber-physical infrastructure (multi-stack reference architecture), modeling methodology for system integration, standards, methods, and protocols for real-time data analytics, and, metrics and assessment methods that will assure the performance of dynamic production systems with a predictable degree of uncertainty.

Many of our research results and publications from the Sustainable Manufacturing Program have good scientific relevance to this new program. The measurement science results and associated tools produced by Sustainable Manufacturing Program were published in reputed peer-reviewed journals and influenced the standards committees, especially ASTM E60.13[3]. Many of the fundamental measurement science results from sustainable manufacturing program, including information models, process characterization, and standards will be expanded to Performance of Smart Manufacturing System program. Also the associated tools and methods, especially the testbed, and simulation and optimization will be expanded to include data analytics, and performance assurance.

1. INTRODUCTION

Traditionally, manufacturing industries are concerned with quality, cost, and productivity. The new dimension added to these as a business megatrend [4] is sustainability [5]. Industry needs a trusted system of metrics and the underlying measurement science to compute those metrics [6]. Standards enable repeatable and improvable processes and as such will allow industry to move forward in achieving sustainability goals. To address these needs NIST initiated the Sustainable Manufacturing Program. The program is charged to develop the science and standards for assessing energy and material use at the factory level for evaluating gate-to-gate[7] lifecycle impacts

[3] http://www.astm.org/COMMIT/SUBCOMMIT/E6013.htm

[4] The Sustainability Imperative by David A. Lubin and Daniel C. Esty, Harvard Business Review, May 2010 & Megatrends: Ten New Directions Transforming Our Lives, John Naisbitt, Grand Central Publishing (August 16, 1988)

[5] The notion of sustainability is broad and in this program we mainly focus on resource (energy, material) efficiency, and waste reduction across the lifecycle of a manufactured product.

[6] Corporate Sustainability-A Progress Report, KPMG and Economic Intelligence Unit, The Economist, April 2011.

[7] Cradle-to-gate is an assessment of a partial product lifecycle from resource extraction (cradle) to the factory gate. Gate-to-gate is a partial Lifecycle Assessment (LCA) looking at only value-added process in the entire production chain. The gate-to-end-of-life step considers both the use phase and the disposition of the material at the end of a product's life. In this phase of the SM program we will focus on design to manufacturing of a product for gate-to-gate lifecycle analysis and synthesis. In the latter phases of the program we will include cradle-to-gate and gate-to-end-of-life studies.

of manufacturing. The program team consists of researchers from the NIST Engineering Laboratory as well as external researchers from universities and research organizations.

In November 2012 a Kick-off meeting for the program was held at NIST. The purpose of the workshop was to focus the upcoming research on the measurement science issues for sustainable manufacturing. The Sustainable Manufacturing Program plan and structure were presented to all members of the newly formed team. The researchers had the opportunity to present their research contributions to the program leading to better coordination of their efforts and focusing on outputs, outcomes and, impacts. The workshop agenda included an introduction to the program: its goals, objectives, structure, and milestones. This was followed by presentations by all the researchers involved in the program on how their work applies to the common challenge problem of measurement science for Sustainable Manufacturing. To this end a set of challenge questions was sent out before the workshop for consideration by the researchers. These same questions focused breakout group discussions at the workshop. Researchers also were invited to contribute written responses to the questions after post-workshop reflection. This report summarizes the workshop and resulting recommendations.

1.1 Overview of Sustainable Manufacturing Program

The Sustainable Manufacturing Program will develop a methodology for the science and standards for assessing energy and material use at the factory level for evaluating gate-to-gate lifecycle impacts of manufacturing. The methodology will enable the computation of energy efficiency and material efficiency across different product lifecycles. Ensuring resource efficiency requires an integrated systems approach and spans across lifecycle issues. Interactions within and across these issues are critical to the fundamental understanding of sustainable manufacturing, because focusing on any single issue could result in suboptimal solutions and unintended consequences. Challenges come in the form of what to measure and how to measure it, what to estimate and how to estimate it, how to reconcile measurements into aggregate and comparable units, and how to optimize the system as a whole. Also, the necessary standards to represent and report the information used and processed by these methodologies need to be fully identified and developed.

To address these needs, this program is organized into two thrusts: methodology and integration. The first thrust will develop a methodology for analysis and synthesis of the energy and material footprint at the factory level for gate-to-gate lifecycle assessment (LCA). To enable this factory-level methodology, the program will develop additional methodologies for characterizing unit manufacturing processes, and product assembly processes. Additionally, the program will investigate how these metrics can be made available for design time decision making. To verify and validate these methodologies, the integration thrust will develop sustainability modeling and optimization techniques and a testbed based on real manufacturing use scenarios. The following summarizes the work of the program as was presented at the workshop:

Thrust One: Methodologies for Characterizing Sustainable Processes and Resources

- **Sustainability Metrics for Design and Manufacturing**:
  1) Develop a generic product structure to support smart process decisions
  2) Develop methods for integrating material properties into downstream life-cycle processes
  3) Define an approach for developing a standard reference vocabulary to support sustainable manufacturing
- **Sustainability Characterization for Unit Manufacturing Processes**:
  1) Develop assessment methodology for characterizing unit manufacturing processes (UMP) with respect to energy and materials
  2) Define a well-defined procedure to characterize any specific manufacturing processes to build a repository of UMPs
  3) Facilitate the development of a structured information base by enabling a Standard Reference Model for Unit Manufacturing Process (SRUMP)
- **Sustainability Characterization for Product Assembly Processes:**
  1) Develop assessment methodology for characterizing assembly processes with respect to energy and materials
  2) Define a well-defined procedure to characterize any assembly process
  3) Compute and include any material or energy impacts associated with production networks

Thrust Two: Integration Infrastructure for Sustainable Manufacturing

- **Sustainability Modeling and Optimization:**
  1) Develop a formal process representation of industrial scenarios
  2) Develop the framework that integrates multiple standalone methodologies and associated applications for assessing and reporting sustainability information.
  3) Develop a framework for sustainability modeling and optimization

- **Testbed for Sustainable Manufacturing:**
  1) Develop real industrial manufacturing scenarios at the factory level, developed through industry collaborations
  2) Synthesize a methodology for testbeds based on prior experiences at NIST and propose a reference testbed architecture
  3) Demonstrate the program deliverables through the testbed, deploy the metrics and measurement science, and assess sustainability performance

1.2 Workshop Challenge Questions

The state of the art for assessing the impact of manufacturing activities revolves around industry-wide average measurements, isolated detailed studies, and extemporaneous public policy. We aim to create a more science-based methodology. An analogy that can be used is to defining the yardstick for sustainable manufacturing. The basic measurement science addresses what to measure. Aggregation of measurements establishes common units of measurement (i.e., how big is a unit, how do units fit into larger units like inches go into feet go into yards). Implementation considers how to create the measurement device. Unlike the one-dimensional yardstick, the measurement device in this case will be multidimensional. The fundamentals of the models that form this multi-dimensional yardstick need to be established. Finally, testing and validation establishes that the science works given real world scenarios and that data on which it is based can be adequately measured.

Much focus has been given to trying to define and measure factors which appear to be related to sustainability, but the resulting definitions are often qualitative or contradictory, the measurements are often scattered, and the reliability of the data is questionable. Hence the end result is often very uncertain. A set of challenge questions which explore the fundamental issues for a more rigorous methodology formed the basis of technical discussions at the workshop. The solutions to these questions will help to create the methodology. These questions, which address the breadth of factors to be measured and the reliability of the measurements, are divided into four areas:

- basic measurement science
- aggregation of measurements
- implementation of measurement science
- testing and validation

The measurement science research and services that are critical in support of this methodology include:

- development of performance metrics, measurement and testing methods, predictive modeling and simulation tools, knowledge modeling, protocols, technical data, and reference materials and artifacts
- inter-comparison studies and calibrations
- evaluation of technologies, systems, and practices, including uncertainty analysis
- development of the technical basis for standards, codes, and practices—in many instances via testbeds, consortia, standards and codes development organizations, and/or other partnerships with industry and academia

The following is the list of questions that were posed in this context to initiate discussion around some of the most challenging issues. The workshop organizers invited participants to present their work in this context as well. It was not required to address all the questions but rather to highlight appropriate work in the context of the questions most suitable.

Basic Measurement Science

- ***To assess sustainable manufacturing what parameters should be measured to compute resource efficiency in terms of energy, material, and water?***

This question addresses what factors should be measured and how to establish baseline and boundary conditions for measuring manufacturing resources. These factors serve as a baseline in assessing the trade-offs of the system as it is optimized. Boundary conditions reflect sensitivity issues in the nexus of energy, material, and water modeling and optimization. For example, are there thresholds for any one of the three resources beyond which the demand on one of the others is dramatically impacted? Finally, the question addresses models or modeling approaches that use actual measurements to improve the overall efficiency of the system.

- ***What are the key factors that contribute to uncertainty in sustainable manufacturing? How can we prioritize these and what measurement techniques can be applied?***

Measurement techniques might address the level of granularity of measurements, frequency of measurement, and level of uncertainty in the data. First we need fundamental research to develop and demonstrate such techniques before proposing standards for these measurements. Such techniques should also address the concern of how to handle the uncertainties and errors associated with sustainable manufacturing indicators from unit processing through the enterprise level. Techniques are also needed to address the flow of information from the supply chain and to validate the data reliability and provide data traceability. In addition, this question may address the integration of Lifecycle Inventory (LCI) data, which represent industry averages, with more local measurements (such as plant-specific).

Aggregation of Measurements

- ***How would a material model that supports sustainability decisions be formulated?***

Given that material information is pervasive in product design and manufacturing, it provides a solid foundation on which to establish the metrics for sustainability. At the same time it provides a link from the virtual world of design to the physical world. This question addresses what a model of material information would look like to support sustainable design choices. In particular, the properties that best capture the information needed to make sustainable material choices need to be identified and organized in a systematic way, perhaps being characterized across material types. Material information in product development is quite broad. The scope of a model to support sustainable design and manufacture would be unique yet would need to interoperate with the wide range of material models that already exist. Approaches for presenting the sustainability information about materials also need to be explored.

- ***How can sustainability data for a manufactured part or assembly be aggregated to enable sustainability analysis?***

Energy use, for example, is a primary factor influencing sustainability but energy use is difficult to gauge in a complex or even relatively simple manufactured good. The production includes the energy used by the facility, energy used by different machines and processes, energy used in producing and transporting component parts. All of these measures contribute to the assessment of energy use for a particular item and yet standards for how that use is apportioned and totaled do not exist. When we expand the scope of sustainability indicators beyond energy use, the order of complexity of this analysis problem grows dramatically. This challenge is compounded by the fact that different processes may have characteristics unique to them. What are these characteristics, how can they be normalized? Furthermore, the accuracy and integrity of measurements is difficult to verify. Techniques are also needed to address the flow of information from the supply chain and to validate the reliability of and provide traceability.

Implementation of Measurement Science

- ***What are the information modeling concepts that are unique to sustainability characterization and optimization?***

Traditional modeling approaches were developed without an emphasis on sustainability needs. This question explores what is available today and how it can be used and what else is needed in terms of basic modeling capabilities to support sustainable manufacturing. Some existing techniques (such as conceptual modeling, information, programing, scripting, and modeling languages, optimization, or simulation) may be extendable to support sustainability analysis; new techniques may need to be developed to do trade-off analysis. Are there techniques that allow extensible modeling to address domain-specific modeling requirements?

- ***What are the characteristics of an effective manufacturing-focused sustainability assessment methodology?***

Sustainability assessment methodology (also called impact evaluation methods in LCA) is an important area of research. Many divergent methods are emerging. This question addresses whether there are fundamental characteristics common across methodologies and what makes a methodology successful.

Test and Validate Measurements and Standards

- ***What are requirements and challenges for a shared research testbed and what types of things could be tested there?***

We are planning for a national facility that would serve as a sustainable manufacturing testbed, which would be used by outside organizations including researchers, industry, and software vendors. This virtual facility would be available for developing and testing the standards and measures that will support a sustainable manufacturing infrastructure. The facility will serve as a platform for validating the emerging standards supporting sustainable manufacturing and allow collaborators to work together in a neutral environment to showcase how the standards work. This question addresses how such a facility might be useful, what requirements there are for a facility of this kind, and any research issues or lessons on testbed development that might benefit this project.

2. WORKSHOP DISCUSSION

Two breakout groups were held during the workshop to discuss the topics of the challenge questions. Both the breakouts and the participants were divided based on the program thrust areas with each group of participants addressing both of the topics separately. A summary of the discussions for each challenge question follows. Participants were also invited to submit written responses to the challenge questions following the workshop. These inputs are included in appendix A. All the material was used to formulate the workshop recommendations in section 3.

QUESTION 1: To assess sustainable manufacturing what parameters should be measured to compute resource efficiency in terms of energy, material, and water?

This question addresses what factors should be measured and how to establish baseline and boundary conditions for measuring manufacturing resources. These serve as a baseline in assessing the trade-offs of the system as it is optimized. Boundary conditions reflect sensitivity issues in the nexus of energy, material, and water modeling and optimization. For example, are there thresholds for any one of the three resources beyond which the demand on one of the others is dramatically impacted? Finally, the question addresses models or modeling approaches that use actual measurements to improve the overall efficiency of the system.

The following points were raised in this discussion.

- The discussion of what parameters should be measured quickly moved to how to normalize measures. Both breakout groups discussed how metrics could be normalized and agreed that metrics could not be compared without normalization. Different ideas that emerged were measurements in terms of mass efficiency, waste, term of use, measures per part, measures per value added, GHG. The only agreement that seemed to emerge on this topic was that no single normalization approach would be appropriate but that normalization would need to be defined in terms of other sustainability goals. Metrics would depend on the point of view of the person doing the measurement. Optimizations can be done for whatever the metric is--when you decide what to measure, you are also deciding what you will optimize. There also seemed to be agreement that no single factor could stand in isolation as a metric but that metrics need to be defined in functional terms which would factor in trade-offs.
- The idea of developing a set of benchmarks as a basis for measurement was discussed. The benchmarks would define a baseline against which sustainable improvement could be measured. Benchmarks would need to be organized in some way such as product class, energy use, process efficiency, or activity.
- A dichotomy was identified as follows:
    - completeness of measurement--such as complete accounting of energy and material for a factory producing an average per unit of product
    - measuring a single variable and how it varies in the context of controlled parameters. It was argued that this latter approach was a better approach for sustainability improvement.
- There seemed to be agreement that a process taxonomy including terminology definitions would be extremely useful. Standard definitions for processes would enable clearer definition of metrics. Apparently some work has been started on that from NRC.
- The discussion centered on material efficiency – initial discussion was on unit mass. However, when you compare different processes this may not make much sense as additive manufacturing may be completely different from powder injection molding.
- Alternative materials may lead to design changes and hence one should capture these changes in material efficiency
- The variations on processes leads to the need for defining process taxonomy
- The DIN and NRC Classifications were touched upon

- Discussion touched on what is the definition of “Waste.”
- The group felt that we need to define material efficiency on a process basis

QUESTION 2: What are the key factors that contribute to uncertainty in sustainable manufacturing? How can we prioritize these and what measurement techniques can be applied?

Measurement techniques might address the level of granularity of measurements, frequency of measurement, and level of uncertainty in the data. First we need fundamental research to develop and demonstrate such techniques before proposing standards for these measurements (which we do intend to do.) Such techniques should also address the concern of how uncertainties and errors associated with sustainable manufacturing indicators at unit process through enterprise level are best handled. Techniques are also needed to address the flow of information from the supply chain and to validate the data reliability and provide data traceability. In addition, this question may address the integration of Lifecycle Inventory (LCI) data, which represent industry averages, with more local measurements (such as plant-specific).

- As what needs to be measured was not clear very little discussion was there on uncertainty
- Uncertainty in measurement seems to be heightened by the fact that in a real scenario there will always be some "missing" or unmeasured data. Any measurement approach will need a way to account for missing data or input errors. There was also a discussion of the reliability of measurements as an accurate representation over time since any single measurement is really only a reflection of the circumstances in which it was taken. Any model developed to account for these factors, providing theoretical values obtained via computation, must itself be evaluated for quality.

QUESTION 3: How would a material model that supports sustainability decisions be formulated?

Given that material information is pervasive in product design and manufacturing, it provides a solid foundation on which to establish the metrics for sustainability. At the same time it provides a link from the virtual world of design to the physical world. This question addresses what a model of material information would look like to support sustainable design choices. In particular, the properties that best capture the information needed to make sustainable material choices need to be identified and organized in a systematic way, perhaps being characterized across material types. Material information in product development is quite broad. The scope of a model to support sustainable design and manufacture would be unique yet would need to interoperate with the wide range of material models that already exist. Approaches for presenting the sustainability information about materials also need to be explored.

- There was significant discussion of the role of PCRs and whether an equivalent method could be defined and used for process. The sense was that process was of such a different nature and that it was so tightly coupled with other factors that there would be no equivalent.

- There was reference to quality standards for products and relating them to aggregating measurements both in a deterministic and non-deterministic sense
- The EPD and PCR (product category rules) were offered as possible ways
- Different views (services) may help in aggregating measurements and building metrics
- Material model should
    - account for decision space for alternatives,
    - an assessment metric should be expressed as a function of control variables to represent trade-offs,
    - factor in "costs" associated with the material from other life-cycle phases (e.g. material sourcing and material use) along with traceability to the other phase
    - to fit to SPAF structure should include a library of metrics, association to process model, expressions of material consumption.

QUESTION 4: How can sustainability data for a manufactured part or assembly be aggregated to enable sustainability analysis?

Energy use, for example, is a primary factor influencing sustainability but energy use is difficult to gauge in a complex or even relatively simple manufactured good. The production includes the energy used by the facility, energy used by different machines and processes, energy used in producing and transporting component parts. All of these measures contribute to the assessment of energy use for a particular item and yet standards for how that use is apportioned and totaled do not exist. When we expand the scope of sustainability indicators beyond energy use, the order of complexity of this analysis problem grows dramatically. This challenge is compounded by the fact that different processes may have characteristics unique to them. What are these characteristics, how can they be normalized? Furthermore, the accuracy and integrity of measurements is difficult to verify. Techniques are also needed to address the flow of information from the supply chain and to validate the reliability of and provide traceability.

- aggregation of metrics requires a common denominator in order to aggregate up
- in aggregation care should be taken to avoid double accounting
- regression analysis could be applied to account for missing detailed measures, how to aggregate shared resources, create analytical formulation and find consumptions averages per machine

QUESTION 5: What are the information modeling concepts that are unique to sustainability characterization and optimization?

Although several of the SM and collaborator presentations showed an information model of a manufacturing process to be used as the basis for analysis, most of the models seemed to be consistent with a process-based LCA modeling structure. Many different information models were mentioned. It was suggested that it would be better if there could be one model. If there are different models, it should be possible to translate from one model to another. Other topics discussed included

- To what level of granularity should equipment used in manufacturing processes be modeled (machine vs. component)? Does the answer depend on what kind of analysis is going to be performed?
- The program should consider supporting Fate and Transport modeling for manufacturing facilities.

QUESTION 6: What are the characteristics of an effective manufacturing-focused sustainability assessment methodology?

The following points were raised as important characteristics for an assessment methodology:

- The modeling and representation of manufacturing processes may differ depending on the phase of manufacturing that is being modeled/assessed.
    - Product design
    - Process design
    - Manufacturing system/production design
    - Production operations
- It might be better to first focus on analyzing one fixed process plan for a product and then move on to analyzing a processes plan with many alternatives.
- Different advanced decision making techniques (such as AHP) should be explored but their feasibility should be weighed against what manufacturing end users will accept.
- The methodology should be general. When applied to different case studies, different weights may be used to compute the metrics supported by the methodology.
- It was suggested that the methodology support a holistic sustainable manufacturing analysis (note: the focus of the SM program is economic and environmental analysis of gate-to-gate manufacturing processes)

QUESTION 7: What are requirements and challenges for a shared research testbed and what types of things could be tested there?

The following points emerged as requirements for a research testbed:

- One real product scenario should be selected to be the basis for all of the SM projects research and demonstrations.
- The testbed and testing requirements should come from
    - All SM projects
    - Industry partners
    - SW application vendors

  (Note: this is the approach that is being undertaken by the testbed project)
- The testbed should be designed to use a virtual representation of a manufacturing facility and its processes.
- It is ok if some of the data collected is be of differing quality (measured vs. computed) as long as it is recognized that this will affect the uncertainty of any analysis results.

- It would be nice if the testbed would provide the data collected from various studies so that SMEs could come in and use it as a basis for analyzing their operations.
- The testbed should not be general but designed to support real manufacturing case studies.

3. WORKSHOP RECOMMENDATIONS AND TECHNOLOGY ROADMAP

The workshop brought together NIST research staff and the research partners to define a common vision for the measurement science needs for sustainable manufacturing. One result of the workshop was a technology roadmap for sustainable manufacturing methodologies.

3.1 Proposed Drivers of Sustainability Evaluation

A focus of the Sustainable Manufacturing Program is to create solution methodologies in the two thrust areas: (1) Methodologies for characterizing sustainable processes and resources, and (2) Integration infrastructure for sustainable manufacturing. Information requirements for each of the two thrust areas are further subdivided.

A synthesis of the information requirements calls for the development of fundamental and generic product, material and process related information and computational models, which include:

1. A formal representation of product structure and assembly that integrates material and process information, so that well-defined procedures and assessment methodologies could be used to characterize the sustainability metrics with respect to energy and materials,
2. A comprehensive material and process model to support sustainability evaluation for any downstream lifecycle processes,
3. A framework for sustainability modeling and optimization (including the development of a standard reference vocabulary to support sustainable manufacturing, and
4. A testbed for assessing sustainability performance.

3.2 Technical Challenges

The benefits of the above mentioned sustainability program are difficult to assess at this juncture, so it is very important that we acknowledge to be aware of the potential challenges that lie ahead of us in implementing the proposed themes. The workshop participants brainstormed and identified a few pertinent research objectives that needed immediate attention in order to achieve the sustainable manufacturing research goals. Following is a list of technological issues that were discussed in detail in the workshop:

Issue #1: Development of information models: three main information models related to product/assembly, materials and processes have been discussed. The questions are: do they cover all necessary information required for sustainability analysis? Should these three models be kept separated or be integrated into one? If they are kept separated what should be the information exchange procedure between these models?

Issue #2: What are the information modeling concepts that are unique to sustainability characterization and optimization?

Issue #3: To evaluate sustainability, what parameters need to be measured (and how) to compute resource efficiency in terms of energy, material, and water? What are the other characteristics of an effective manufacturing-focused sustainability assessment methodology? What are the sources of uncertainty and how to deal with them? How can sustainability data be aggregated for sustainability analysis?

Issue #4: How the product, assembly, materials, and process information models be validated? What are the requirements and challenges for developing a shared research testbed?

These issues and suggested solutions in terms of a research roadmap are presented in the next section.

3.3 The workshop recommendations and a research roadmap

The input from the workshop and follow up work resulted in the following roadmap for future action for the program.

Development of an Integrated Information Model:

The workshop participants concluded that it would be better if there could be a core model for product/assembly, materials and processes. The model should be modular and extensible. It must support all pertinent information that may be required for sustainability analysis at any given stage of the product's lifecycle.

While the material usage and energy efficiency assessment are two critical factors in sustainability evaluation, the granularity of material and process information contents are most important and they need to be carefully modeled in different abstraction levels as required. Material information is needed in every phase of the product's lifecycle activities, starting from design to disposal of the product; and the nature of material information requirements changes with each lifecycle activity. For example, in a bottom-up design approach, one may seek to match up the product's performance requirements with a material's intrinsic properties (which are functions of a material's atomistic structure); whereas, in a top-down design approach, a designer may want to design a new material that will suit a product's functional requirements best (which may need atomistic/meso -level information). The material information model should be able to provide necessary information in both cases. Even at the macro- structure level, the material property is not always well defined. Some of the material properties like creep, fatigue, residual stresses, are time- and/or process- dependent, which necessitates developing appropriate operating environments and process information models being coupled with the material model.

Another important fact of the material information model is that it must be tightly coupled with a product's form and function models, and its manufacturing process information model. It is a well-known fact that material properties may change considerably at the end of a manufacturing process sequence that in turn, may affect the product's function. For instance, in the aerospace industry, casting and forging operations are often used to manufacture the initial part shape. Both casting and forging introduce unwanted stresses in the part, which in subsequent machining stages can be a source for severe part distortions and ultimately part rejection due to failure to achieve the geometric tolerance/accuracy required. Another example is in the case of heat treatment processes, which are deliberately used to alter the material properties. Therefore, an appropriate behavioral model for materials needs to be associated with the materials information model. This adds to another dimension to the materials information modeling structure; the issue is how to make the behavior model available (and there are a wide range of different computational material models currently available, which could be safely grouped under the material behavior model) for multi-scale modeling. There is a y benefit in developing physics-based computational tools for predicting the behavior, and influencing the design of nanostructured materials such as high-performance polymers, composites, nanotube-reinforced polymers and other smart materials.

The question is how to couple this complex set of materials information models with manufacturing process models. The workshop participants foresee that the real challenge in developing the material information model, which is sufficiently flexible and dynamic, lies in the data structure and ontologies used in the overall system architecture.

Now what about the manufacturing process model? To facilitate the material and energy efficiency assessment, the manufacturing process model must provide (i) required information related to equipment and process parameters, process consumables and facility overhead charges, process wastes, and (ii) required process information to specify material property/behavior at the end of a given manufacturing process sequence. It will be very useful if the manufacturing process information could be specified at multiple levels of detail – supply chain, manufacturing facility, line, department, cell level, and machine level. This will help in tracking down the material and energy wastage.

Sustainability Characterization and Optimization:

For sustainability characterization, it is suggested that the information modeling concept should capture and establish relationships between intermediate material information (of shape, size, form feature, and surface property and its energy (as well as other consumables such as tooling, lubricants, and coolants) consumptions in each step of the manufacturing process sequence. It should also profile emission in the same manner.

For sustainability optimization, alternative process plans with different resource requirements and process parameters should be evaluated.

The above modeling methodology will work fine for a "fixed" chain of processes (which are characterized by fixed output quantities and fixed process control parameters); any total amounts of energy, material, and water usage can be measured by appropriate metering techniques. If the processes are not "fixed" (when both control parameters and outputs vary), *function*s (instead of constants) of energy, material, and water consumption need to be formulated in terms of output demands and process control parameters. These *function*s could be developed either by using the black-box design approach or by using the white-box approach. A black-box design approach starts with assessing the analytical form of an assumed *function,* and then looking at operational input points and the corresponding values of energy, material, and water usage over time, and regressing the *function* (the regression analysis technique). Following the white-box approach, one would decompose a process into sub-processes, try to model and estimate the energy, material, and water usage *function*s of the sub-processes, and compose the global *function* for the entire process. If needed, a mixed approach trading-off between the level of process decomposition (into its sub-processes) and dimension of the regression problems could also be adopted in assessing the sustainability indices. In either case, it is not a simple exercise and it needs extensive modeling and model validation efforts.

Sustainability Assessment Methodologies:

Several researchers have advocated the necessity of a detailed identification of important parameters for assessing energy, material, and water consumption/wastage. Broadly speaking, energy consumption (kWh) needs to be evaluated:

1. for different manufacturing processes and their equipment, including material, product handling systems (the workshop participants came up with a list of several important process variables that directly or indirectly affect energy consumption in the manufacturing process. It was suggested that NIST consult with other federal/state research initiatives which are already made some progress in this area – See Appendix A),
2. for any other auxiliary equipment that have not been considered in (i) (e.g., auxiliary lubrication system, and cooling system),
3. for energy consumption during machine idling (when the machine tool is in standby mode with its peripheral units turned on) and traversing (when the machine axes and spindle are in motion without any metal processing), and
4. during the manufacturing process setup periods (energy consumption during setup could be substantial in case of larger and heavier part processing). Production efficiency and overall equipment effectiveness (including equipment availability, performance efficiency, process utilization, and product quality) could be other metrics for energy consumption assessment.

For material consumption assessment, the assessment parameters could be amount of material usage including raw material use, raw material consumption (chips), and raw material wastage (scrap). Additional material parameters could be other process consumables including cutting tool consumables, engineering tooling consumables (e.g., mold and dies), device consumables (e.g., jigs, fixtures, and pallets) and lubricant consumables to name a few. Waste material filtration, treatment and their handling for used lubricants, coolants, and/or other toxic, hazardous materials could be other significant factors in assessing the energy and material efficiency.

For evaluation of water consumption, filtration and treatment of hazardous materials have significant contribution. Other factors include water consumption in manufacturing processes like the use of water in the form of coolant or cutting fluid during any machining operation.

However, collection and aggregation of the data to provide an overall sustainability assessment of a part, assembly or a process could be difficult. A performance index that covers energy, material, and water efficiency, and other manufacturing footprints (including harmful emissions and waste) could be considered. Generalization could be difficult, especially considering the long supply-chain that may exist for a complex assembly. Some suggested that the use of a normalization method of the sustainability data and use of a weighting method (like the eigenvector, weighted least square or entropy method) as it has been applied in other engineering fields. Others argued that the characteristics of a sustainable company, process or part could vary greatly across each of these categories. In each case, the resources used to make the product (e.g., energy), the value added to the product (could be measured with cost), and lifecycle impacts should be considered to accurately assess sustainability.

It brings up the question of how to characterize the sustainability assessment methodology itself. An effective methodology must meet the general criteria of desirability, operability, practicability and repeatability. It should be easy to use and inexpensive. It should be practical enough such that a corporate user can readily apply it to one of its corporate business units for a specific product (group) in a lifecycle phase, after selecting sustainability manufacturing performance indices, reference data set, and assessment techniques. All data must be contextualized with process information. The assessment methodology will have to incorporate some degree of flexibility to cater different needs of various sectors and technologies. The researchers also realized that there were inherent uncertainties present in data collection and data analysis.

There are uncertainties based on measurement techniques used and due to the inherent variability of the processes. There could be other sources that may lead to uncertainty problems: (i) lack of direct measurements of the parameters of interest, (ii) lack of understanding regarding what drives parameters (often due to lack of knowledge in process information), (iii) lack of understanding how to analyze data that has been collected. Other indirect factors like lack of sufficiently quantifiable information, uncertainty in government rules and regulations may create problems in identifying correct data. When it comes to computation of metrics (quantitative models or equations), many other factors could contribute to the uncertainty of manufacturing sustainability, such as variations in setting operational parameters, and the machine model. It would require a tremendous amount of coordinated efforts to build an appropriate database necessary for the implementation of a sustainability assessment methodology in order to support a range of materials and their associated processes, using various machine and equipment resources.

Validation of the Information Models Using a Shared Research Testbed:

The main requirements of a shared research testbed would be: (i) to demonstrate integration and implementation of the three core information models for product, material and process (PMP) coherently, and to show how to retrieve the information required for sustainability assessment at any stage of the product lifecycle; and (ii) to showcase the usability of the core information model for some benchmarking problem(s). It should help demonstrate the most important requirements of sustainability-related assessments and standards within the product's lifecycle framework. The benchmarking problems or case studies should come from a multitude of industries that encompass a range of discrete products so that an assortment of processes could be tested. The testbed must mimic the process of interest as closely as possible and would allow testing of a large number of parameters to compute resource efficiencies in terms of energy, material, and water.

The type of things tested should start from basic manufacturing process steps on simple products and be enhanced gradually to complex processes on complex products. Initial analysis may be based on product flow modeling. Later engineering process simulation models may be included that allow testing of detailed unit process parameters and modeling of assembly operations.

Several challenges have been anticipated in the development of such a national level shared research testbed. The problem could be: (i) in determining which processes to test: it should be determined based on product volume, value added and/or other considerations, and (ii) in protecting the security of company data and proprietary information: it may create problems and needs to be sorted out with the individual company on a case-by-case basis.

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Disclaimer

Certain commercial software products are identified in this paper. These products were used only for demonstration purposes. This use does not imply approval or endorsement by NIST, nor does it imply these products are necessarily the best available for the purpose.

Appendix A: Inputs from the Participants

The following discussions were provided by the researchers following the workshop and after reflection on the workshop discussions. The text is presented exactly as it was submitted without editing for synthesizing.

Soundar Kumara, Christopher Saldana and Qais Al-Khazraji, Penn State

Overview: This workshop focused on understanding the foundations required for measurement science to characterize resource (energy, material) efficiency and facilitate waste reduction across the production lifecycle (gate-to-gate) for manufactured products. Most of the project leads (except UMD) participated in the effort. The project leads as well as the researchers at several organizations and at NIST are employing a host of approaches to tackle the problem of sustainability assessment. The one-and-half-a-day workshop focused on several issues. This document summarizes the deliberations.

Summary: The central issue for the workshop and the challenge posed by the NIST lead (Dr. Rachuri) was the need to establish standards for sustainability assessment by manufacturing organizations. Some important elements involved in making such assessments were highlighted, which include:

1. Understanding what needs to be measured, at which stages of the manufacturing processes should these be measured and how we should measure them.
2. Identify the accuracy and precision of the above extracted measurements.
3. Verify and validate our measurements.
4. Provide the analytical method(s) to aggregate (compose) the individual sustainability measurements into the final sustainability index.
5. Develop standards for the measurements, uncertainties and final sustainability index for the gate-to-gate part of the manufacturing lifecycle.

The development of a material information model was a key topic that was tackled during the workshop. To develop such a model, researchers asked the following questions:

1. Who will use the material information model during the lifecycle of the product? What is the main focus of such a model? How do we capture material information models for different material classes that essentially use different manufacturing processes?
2. What will be the terminology/taxonomy for these material information models?

For every product, the manufacturing sequence is a combination of different unit manufacturing processes. Several researchers highlighted that material information models must provide the linkages between intrinsic/extrinsic material information and manufacturing process metrics and this data must be made available during early product design stages for the model to be of maximum use. They claimed that this would enable designers to select alternative materials based on sustainability from a production viewpoint. This material information model should also be useful in developing optimization methods for production sequencing and process selection.

It was argued that effective capture of all relevant sustainability information would require that the material information models be rooted in the description and classification of these unit manufacturing processes. The real challenge in developing a material information model that is sufficiently flexible for capturing every unit manufacturing process lies in the data structures and ontologies used in the overall system architecture. Further, the lack of existing measurement science (standards) and lack of consistent information representation for unit manufacturing processes are two problems that some researches addressed as key concerns in this regard. For example, some researchers argued that it is unclear how "deep" one must go into modeling the machine components, machine settings and the tool settings in order to analyze the sustainability elements of each unit manufacturing process.

Another concern that was raised during the workshop was that factors such as material information, product functionality, part geometric features, and process parameters are interrelated since all of these (including material properties) can be changed as a consequence of the manufacturing processes selected. Therefore, the material information model should also facilitate tracing of mechanical and physical material property changes during each unit manufacturing process. Therefore, the material information model, at some level, must be designed to be dynamic and not static in nature.

While the material information model will provide capability to assess unit manufacturing processes for individual sustainability indicators, a major focus of the discussion and a source of contention amongst the researchers was the development and potential validity of a generic analytical model to calculate an aggregate sustainability index for multiple unit manufacturing processes in an overall production sequence. One major point regarding the validity of an aggregate approach was the importance of being able to model/capture the benefit of alternative designs/material selection in specifying the gate-to-gate sequence of processes. For example, different processes have different benchmarks, the researchers discussed the need to define these benchmarks and have a standard level to compare other manufacturing sustainability indicators with their relative benchmarks.

In this regard, several researchers indicated that decision of the appropriate metrics, design of scientific measures to calculate the resource efficiency (e.g. normalization routines) and how to aggregate these metrics to supply the aggregate score are all highly coupled to the role of the person (or company) making the lifecycle assessment. Thus, any aggregate score will have to incorporate some degree of flexibility in definition to facilitate the various users possible and weighting of the metrics appropriate for those sectors/technologies. From an information architecture standpoint, the various users/participants (or services) may have interest in different stages or granular viewpoints of the gate-to-gate lifecycle. This will likely modulate the functionality required to direct sustainability data to each of these services.

As some of these questions were being addressed, the suggestion was posed to the group to utilize case studies to help draw out the most important requirements of sustainability-related assessments and standards within the gate-to-gate lifecycle framework. These case studies should come from a multitude of industries that encompass a range of discrete products, ranging in technology levels used in manufacturing as well as in the inherent economic unit value of the product.

<u>Action items from PSU:</u> Respond to 7 breakout questions.

1) To assess sustainable manufacturing, what parameters should be measured to compute resource efficiency in terms of energy, material and water?
2) What are key factors that contribute to uncertainty in sustainable manufacturing? How can we prioritize these and what measurement techniques can be applied?
3) How would a material model that supports sustainability decisions be formulated?
4) How can sustainability data for a manufactured part or assembly be aggregated to enable sustainability analysis?
5) What are the information modeling concepts unique to sustainability characterization and optimization?
6) What are characteristics of an effective manufacturing-focused sustainability assessment methodology?
7) What are requirements and challenges for a shared research testbed and what things could be tested here?

Dave Dornfeld, University of California Berkeley

1. To assess sustainable manufacturing, what parameters should be measured to compute resource efficiency in terms of energy, material, and water?

The parameters below were developed for a project for the Sustainable Aerospace Manufacturing Initiative (SAMI) [8], which was focused on cutting. Most of these parameters are generally applicable to all manufacturing processes. A few of these variables would need to be translated to be perfectly applicable to manufacturing processes other than cutting, but the translations are relatively straightforward. The units of each variable are generalized unless otherwise noted as follows: *l* represents units of length, *v* represents units of volume, *t* represents units of time, and *m* represents units of mass.

Variable	Name	Units	Value
A_{cell}	Cell footprint	l^2	
A_{avg}	Average cell footprint	l^2	
A_{total}	Total facility floor space	l_2	
CA	Compressed air usage	v	
C_{omp}	Demand on air compressor	%	
E_{HVAC}	HVAC energy	kWh	
E_{light}	Lighting energy	kWh	
h_{cell}	Powered cell time	t	
$h_{facility}$	Total facility powered time	t	
$m_{fixutre}$	Total mass of fixture material	m	
m_{parts}	Total mass of material in all processed parts	m	
$m_{replacement}$	Total mass of replacement part material	m	
n	Noise level	dB	
N_I	Injuries per year	injuries	
$N_{process}$	Process loss per cell	m/t	
P_i	Idle power	kW	
P_p	Processing power	kW	
P_w	Warm-up power	kW	
R_{clean}	Water consumed for cleaning	v/t	
R_{cool}	New coolant oil consumed	v/t	
$R_{cool,r}$	Coolant oil recycled	v/t	

[8] For more information see the final SAMI project report: Sustainable Manufacturing Assessment, GKN Aerospace, submitted February 2011 the by National Center for Defense Manufacturing & Machining.

R_{lube}	Lubricating oil consumed	*v/t*	
R_{water}	Water consumed for coolant	*v/t*	
$S_{savings}$	Lifetime savings	$	
$S_{investment}$	Investment cost	$	
SD	Sick days per year	days	
T	Tool life	*t*, *v*, or parts	
$t_{c,design}$	Cycle time	*t*	
$t_{calendar}$	Calendar time	*t*	
$t_{d,planned}$	Planned downtime	*t*	
$t_{d,unplanned}$	Unplanned downtime	*t*	
t_i	Idle time	*t*	
t_p	Processing time	*t*	
t_s	Operation time	*t*	
t_w	Warm-up time	*t*	
V_s	Production volume	parts/*t*	
V_{scrap}	Scrapped volume	parts/*t*	
V_{rework}	Reworked volume	parts/*t*	
W_{HAZ}	Hazardous waste	*v/t*	
W_{solid}	Solid waste	*m/t*	

1.1 Power demand and energy consumption

Metric	Variable	Units	Value
Idle power demand	P_i	kW	
Warm-up power demand	P_w	kW	
Peak power demand	$P_{p,max}$	kW	
Component power demand	$P_{comp,i}$	kW	
Cutting power demand	P_{cut}	kW	
Processing energy consumption per year	E_p	kWh/year	
Idle energy consumption per year	E_i	kWh/year	
Warm-up energy consumption per year	E_w	kWh/year	

1.2 Production efficiency/overall equipment effectiveness (OEE)

Metric	Variable	Units	Value
Availability	a	%	
Performance efficiency	$\eta_{performance}$	%	
Process utilization	$u_{process}$	%	
Quality	q	%	

1.3 Process consumables and facility overhead charges

Because many of the variables associated with consumables and overhead charges are usually known at the facility level, we must first define a scaling factor that will assign these flows to each cell or machine based on its relative size (larger machine tools or cells generally have larger impact) and processing time (longer processing times generally increase impact). This scaling factor, *K*, has been defined as follows:

$$K = \left(\frac{A_{MT}}{A_{avg}}\right)\left(\frac{h_{cell}}{h_{facility}}\right).$$

This scaling factor should be used with any metric or variable known only at the facility level.

Metric	Variable	Units	Value
Coolant oil consumption	R_{cool}	v/t	
Recycled coolant	r_{cool}	%	
Lubricating oil consumption	R_{lube}	v/t	
Water consumption for coolant	R_{water}	v/t	
Water consumption for cleaning	R_{clean}	v/t	
Tool life	T	t, v, or parts	
Fixturing	F	%	
Replacement parts	R	%	
Compressed air usage	CA	v/t	
Effective compressor energy consumption	$E_{comp,eff}$	kWh	
Effective HVAC energy consumption	$E_{HVAC,eff}$	kWh	
Effective lighting energy consumption	$E_{light,eff}$	kWh	

1.4 Process waste

Metric	Variable	Units	Value
Rework rate	N_{rework}	%	
Scrap rate	N_{scrap}	%	
Process loss	$N_{process}$	m	
Hazardous waste	W_{HAZ}	v/t	
Solid waste	W_{solid}	v/t	

Additionally, more traditional manufacturing metrics remain important in these analyses to ensure that the process remains effective in producing parts that are of sufficient quality. Some of these more traditional parameters are included in the suggestions above (e.g., downtime, tool life), but can also be expanded for additional detail. For example, perhaps the loads on a machine can be an important parameter that relates to the maintenance and service life of that machine. Another example is the surface roughness of the finished part, which may be important because it will dictate the impact of the manufacturing phase on subsequent lifecycle stages.

2. What are the key factors that contribute to uncertainty in sustainable manufacturing? How can we prioritize these and what measurement techniques can be applied?

- Problems with measurement
    - Lack of direct measurements of the parameters of interest (may be linked to a lack of measuring devices)
    - Lack of understanding regarding what drives parameters (often due to disregard for associated process information)
- Problems with existing data analysis
    - Lack of understanding how to analyze data that is collected
    - Erroneous assumptions regarding the applicability of data and analysis (e.g., over generalization)

3. How would a material model that supports sustainability decisions be formulated? Ashby charts may provide a useful framework to follow.

From our perspective, any model should consider all levels of the manufacturing enterprise (i.e., process to machine to cell to line to facility to supply chain) as well as all stages of the lifecycle to avoid offsetting any impacts. Manufacturing energy can already be linked to surface characteristics like roughness (which relates to use efficiency and thus use phase impacts), and other manufacturing considerations (e.g., tool wear, availability) can be both related to processing choices. It seems reasonable that a material model could be developed that follows the same relationships to assess other aspects of sustainability (e.g., material and water usage).

4. How can sustainability data for a manufactured part or assembly be aggregated to enable sustainability analysis?

Aggregating data to provide an overall sustainability assessment of a part or assembly can be problematic at best. The characteristics of a sustainable company, process, or parts can vary greatly across each of these categories. In each case, the resources used to make the product (e.g., energy), the value added to the product (could be measured with cost) and lifecycle impacts should be considered to accurately assess sustainability.

Assuming a specific part or assembly has been identified and considering only energy, two possible measures are:

- Energy per volume (to accommodate fluctuations in volume produced)
- Energy per dollar spent to manufacture the product (to help account for high product mixes)

5. What are the information modeling concepts that are unique to sustainability characterization and optimization?

Information modeling is not our area of expertise, but we would argue that these concepts are important:

- Interoperability to contextualize data
- Multiobjective optimization to balance the different priorities in sustainability

6. What are the characteristics of an effective manufacturing-focused sustainability assessment methodology?

An effective manufacturing-focused sustainability assessment methodology would be composed of three steps

1. Measurement of relevant parameters
    - Present a holistic picture of sustainability of the factory
    - Ensure data at the process level is at the right specificity
    - Data is contextualized with process information
    - All three pillars of sustainability (i.e., environmental, social, and economic) should be considered
2. Characterization of the measured data to obtain information about the process
    - Define uncertainty of analysis
3. Optimization to use the information to improve the process

For steps 2 and 3, the approach should consider offsetting impacts both within the manufacturing phase and between the manufacturing phase and other lifecycle stages

7. What are requirements and challenges for a shared research testbed and what types of things could be tested there?

Requirements

- Test an assortment of processes
- Testbed must mimic the process of interest as closely as possible
- Test an assortment of measurement equipment and tools
- Test large number of parameters (see question 1)

Challenges

- Determining which processes to test
    - Should it be based on production volume, value add, or other considerations?
- Proprietary information
    - Some companies may not want to share manufacturing practices with others.

Uses for testbed

- Identifying and quantifying parameters of importance for specific processes and products
- Identifying and quantifying sources of uncertainty

Rita Schenck, American Center for Lifecycle Assessment

Overall, I was very impressed by the workshop and agree with the feedback/summary from the breakouts.

I think that overall the challenge to metrics for sustainable manufacturing is that the questions of process optimization relate to efficiency of resources to accomplish a process, while the metrics of sustainability relate to maximizing function while minimizing environmental impact. It is a challenge to bring together these two different points of view, i.e., process vs. function. I think the key will be to standardize ways to link process to function. As an example, one might look at all the ways to create a particular chemical. Each pathway has its own needs. Likewise, one might look at all the ways to make a hole (this was an excellent example brought up in the workshop). One can use a hand drill, a cam drill, a laser drill or even a high pressure water drill. They all accomplish the same goal. We can compare energy use and materials loss and emissions for all these different processes, and then evaluate their sustainability for a particular hole or a range of holes we might want to make.

This leads directly to the need to have a standard taxonomy of process types, and they should be arranged by function (e.g. adding material, removing material, changing shape, chemical transformation, cleaning and so forth). The designers of manufacturing equipment then need to have standard ways to test their equipment (drilling plastic, metal, wood, etc.). This information can then be made available in the “lego blocks” that represent the unit processes for LCA. Using the machine shop at NIST we could develop preliminary test for different machines.

The virtue of the Product Category Rules (PCR) is that it can specify the rules for the measurement of a unit process or group of unit processes including a cradle-to-grave set to cover the entire lifecycle. Anything from a single process to an entire lifecycle could be the subject of a PCR. The PCR is a specification for environmental sustainability measurement.

That means that we can take on any level of sustainable manufacturing we would like: we have different options.

As a practical matter, I think it would be a good idea to take on a range of PCRs. I have three examples,

1. We could choose the production of a food container, a relatively simple process. Most of these containers are made of plastic and undergo extrusion or forming and some kind of printing. They can be made of recycled materials and they can be made to be recycled. We could develop a set of PCRs for each of the processes used.
2. As I mentioned in our breakout, I am working with the Sustainable Apparel Coalition. There the unit processes are very different: spinning and weaving and dyeing, and cut and sew operations. This last process is very important to the

financial success of an operation. There are several mills in the Carolinas that we could get to work with us.

3. Finally, another strategy would be to work with the metal-bending kind of operations that are used by the companies that NIST is already working with. I know few companies that are deep into LCA work. They certainly have a broad range of machining operations they could use as testbeds, and some of them they do military work, which could help subsidize the work.

Sanjay Jain, George Washington University

All the questions raised may require short research efforts to answer well. Indeed, most of these questions are being looked into by projects under SM program. We may want to have shared documents on-line for each of these questions that everyone can add to. Below are thoughts on each of the questions.

Basic Measurement Science

1. To assess sustainable manufacturing what parameters should be measured to compute resource efficiency in terms of energy, material, and water?

The parameters would need to be specified at multiple levels of detail – supply chain, manufacturing facility, line/department/cell, and machine level. This will help in tracking down the resources /resource-groups that have lowest efficiency. To allow comparison with other manufacturing organizations, the parameters may be defined per dollar value added – such as, kWh per dollar value added for energy, kg/gram of material used per dollar value added, and kiloliter/liter of water used per dollar value added. The tradeoff among the three measures is expected to be environment dependent. Poor design of manufacturing processes will generally have lower efficiencies on all three measures. There may be tradeoffs on the efficiency frontier among the three measures that can be studied using engineering simulations.

2. What are the key factors that contribute to uncertainty in sustainable manufacturing? How can we prioritize these and what measurement techniques can be applied?

One of the major sources of the uncertainty related to measures for sustainable manufacturing will be due to the resource consumptions in overhead and shared uses for production. For example, the energy used by the administrative staff at the facility will need to be apportioned to the manufacturing output from the facility. There can be multiple approaches to such apportioning (e.g. by weight, by number of units, by number of pallets, etc.) each of which may be most reasonable under certain circumstances.

Of course, there are uncertainties based on measurement techniques used and the inherent variability of the processes, differences due to local measurement practices, etc. It is believed though that the apportioning approaches will contribute a larger percentage of uncertainty and should be addressed first. That is, the priority order for addressing the different sources of uncertainties should be based on the expected amount of uncertainty caused.

Aggregation of Measurements

1. ***How would a material model that supports sustainability decisions be formulated?***

Material options will need to be considered integrated with process options. Change in material will almost always result in change in process parameters, and usually in change in process themselves. A decision tree may be developed that considers multiple material options that allow meeting the product functionality requirements, and for each material option, considers process alternatives that again meet the product functionality requirements (for example, tolerance for machined products).

A standard structure needs to be defined for making apple-to-apple comparison across multiple material options that may be captured using different material model types.

2. ***How can sustainability data for a manufactured part or assembly be aggregated to enable sustainability analysis?***

   As mentioned above in the uncertainty topic, different apportioning approaches for shared resources may be reasonable based on manufacturing environment. Apportioning approaches may be standardized for each PCR category to allow measurements that are reasonable for and comparable across each category.

Implementation of Measurement Science

- ***What are the information modeling concepts that are unique to sustainability characterization and optimization?***

  Most of the current techniques can indeed be extended for modeling additional factors for supporting sustainable manufacturing. Such extensions should be made in parallel with efforts to develop new technologies for the purpose if there are research resources available. For constrained research resources, extensions of current techniques are evaluated first before embarking on new developments.

- ***What are the characteristics of an effective manufacturing-focused sustainability assessment methodology?***

  The key characteristic for assessment methodology is the same as that for any measurement tools – repeatability. That is, application of the methodology multiple times for the same manufacturing artifact by multiple people should lead to the same assessment within an identified uncertainty level. Other characteristics include: ease of use, inexpensive, etc.

Test and Validate Measurements and Standards

- ***What are requirements and challenges for a shared research testbed and what types of things could be tested there?***

In brief, the requirements and challenges include: security of company data, ease of use, security of outputs of testbed, repeatability of assessments generated for each scenario under a defined set of circumstances, and generation/ demonstration of value through assessments conducted using the research testbed.

The type of things tested should start from basic manufacturing process steps on simple products and be enhanced gradually to complex processes on complex products. Initial analysis may be based on product flow modeling. Later engineering process simulation models may be included that allow testing of detailed unit process parameters and modeling of assembly operations

Utpal Roy, Syracuse University

3. ***To assess sustainable manufacturing what parameters should be measured to compute resource efficiency in terms of energy, material, and water?***

In terms of Energy: In Gate-to-Gate (G2G) scenario, we need to evaluate energy consumption (kWh) in (1) different manufacturing processes and their equipment, including material/product handling; in auxiliary equipment (e.g., for lubrication, cooling systems, etc.) (2) Energy consumption during machine idle times, (3) in manufacturing process setup (it is prominent in case of heavy parts/equipment); We also need to account for the general energy consumption in maintaining healthy work environment in the manufacturing facility and the energy consumption for recycling/reuse of lubricants, coolants, etc.

In terms of Materials: In G2G, the combination of the followings: (1) amount of material usage, (2) material waste (may be ratio of material waste/total material usage) (3) recyclability of material waste (4) toxic/hazardous material content identification and handling issues – need to be considered.

In terms of Water:
At least we need to consider:
(1) Water consumption in manufacturing processes.
(2) The hazardous material contents, both in product and manufacturing processing elements must be monitored. Any quantification of the material waste that is going to our water system will be extremely helpful.

4. ***What are the key factors that contribute to uncertainty in sustainable manufacturing? How can we prioritize these and what measurement techniques can be applied?***
   - Lack of information /Missing data
   - Measurement uncertainty
   - Lack of sufficiently quantifiable information
   - Uncertainty in government rules/regulations, market price fluctuation of material, energy, service.

Aggregation of Measurements

3. ***How would a material model that supports sustainability decisions be formulated?***

Material information model must serve in determining: (1) design choices in the conceptual design stage, (2) Material process choices, (3) product/process sustainability indices. Material information model is NOT simply a material property database; it must directly support the sustainable design and manufacturing activities. Information should be readily available in the information model.

In general, I would rather expand the idea of developing a model which is not solely Material –centric but also encompasses the development of an integrated approach towards development of a product/material/process (PMP) –based model; it will distinguish our work from other's works in the field of material information model development. The first step towards it would be to identify first and then classify the information needs for making sustainability-based decisions in different product lifecycle stages. The needs are definitely different at different phases. The information model needs to be developed accordingly.

- ***How can sustainability data for a manufactured part or assembly be aggregated to enable sustainability analysis?***

Some kind of performance index that covers energy and material efficiency, and other manufacturing footprints (including harmful emissions and waste) could be considered. Generalization could be difficult; especially considering the long supply chain that may exit for a complex assembly product. However, I have some reservation about these types of indices. Most of the present indices are formulated on an ad-hoc basis, and are weighted indices that are prone to personal biases. I also do not feel one single aggregated number can truly reflect the sustainability of a product/process.

Implementation of Measurement Science

- ***What are the information modeling concepts that are unique to sustainability characterization and optimization?***

I am biased towards ontology based system.

- ***What are the characteristics of an effective manufacturing-focused sustainability assessment methodology?***

- ***What are requirements and challenges for a shared research testbed and what types of things could be tested there?***

The main requirements of the testbed would be to find a way to: (i) Integrate and implement three predominant information models for product, material and process (PMP) coherently so that information required for sustainability assessment at any stage of the product lifecycle could be readily available; and (ii) showcase the usability of the integrated information model for some benchmarking problem(s).

Alex Brodsky, GMU

- To assess sustainable manufacturing what parameters should be measured to compute resource efficiency in terms of energy, material, and water?
- What is the information modeling concepts that are unique to sustainability characterization and optimization?
- What are the characteristics of an effective manufacturing-focused sustainability assessment methodology?

Suppose we have a manufacturing process M (at any level, e.g., unit, assembly, gate-to-gate etc.), that produces output products in quantities $p_1,...,p_n$, and having control parameters P. If the process if fixed (i.e., fixed output quantities, say daily, and fixed control parameters), then any total amounts of energy, material, and water (a numerical constant for each) can be measured by appropriate metering that would measure totals. In this case however, - we can't attribute amount of energy, material and water to 1 unit of each output product, and - we can't compare 1 process with another, if these processes do not have the same composition and quantities of output products.

If the process is not fixed, i.e., there is flexibility in both control parameters P and the demand for output products varies, then we need to assess functions (rather then constants) E (energy), M (material), and W (water) use in terms of $p_1,...,p_n$, and P. If we can come up with such a function, then we could: - reason about optimal setting of parameters P given demand $p_1,...,p_n$,, and - compare different processes in terms of their efficiency even though they do not have the same composition or quantities of output products (e.g., this can be used for maturity model estimates) - attribute the amount of E, M and W to 1 unit of each output product.

An important question is how to assess these functions. I can think of a black-box approach, and a white-box approach: - a black-box approach would start with assessing the analytical form of this function, and then looking at sample operational input points and the corresponding values of E, M and W measured over time, and regressing the functions, or - a white-box approach, in which one would decompose a process into components, try to model/estimate the E, M and W function of the components, and compose the global function for the entire process One can also consider a mixed approach, that would make a trade-off between the level of decomposition and dimension of the regression problems (to avoid the "dimensionality curse"). This is not a trivial problem, but an important one to solve.

We also need to understand the key factors that contribute to uncertainty in sustainable manufacturing. We need prioritize these and the corresponding measurement techniques have to be developed. If statistical learning techniques (e.g., regression analysis) are used, the selection of an analytical functional form may introduce uncertainty. The other issues include:

- How would a material model that supports sustainability decisions be formulated?

- How can sustainability data for a manufactured part or assembly be aggregated to enable sustainability analysis?

We may want to distinguish the situation when we control a manufacturing process to produce a material, as opposed to the situation when we acquire material and would like to estimate the composition of sub-materials within it.

- the first case goes back to the question of assessing sustainable manufacturing (see above)
- the second case, we can try and use known databases and systems that have information about composition of sub-materials, and then just aggregate.
- a more refined approach for the second case, could be based on Sustainability Product Labels (that Rita talked about), which is an interesting approach.
-

Regarding the requirements for a shared research testbed and the types of things could be tested there, here are three levels of functionality that come to my mind:

- black-box (data-retrieval and/or computational) services, e.g., via web-service mechanism, to publish, search and use services.
- a common database of standardized parts of information models (can be a relational, XML based, Ontology-based or a combination thereof) that can be accessed and modified by the testbed users
- a knowledge base of higher-level abstraction artifacts, such as the sustainable Process Analytics formalism (SPAF) artifacts describing manufacturing processes, flows, metric computation and aggregation, process constraints etc.), and tools (e.g., SPAF enabler) that would allow building of process models, their easy composition, and performing (what-if) analysis, and decision optimization tasks against the process analytics formalism.

Kincho Law, Stanford University

Here are a number of my observations and comments:

We need to develop a roadmap and overview on material information modeling. For the research related to sustainability (energy) characterization of product assembly process (from gate to gate), the research questions are:

- What (the scope) to include in the model – the actual assembly processes, the material handling processes, the transportation/logistic processes?
- How to collect data to validate whatever information models we will be developing to characterize sustainability parameters?
- What testbed shall we use to validate our development?

As an initial step, we also need to review and establish initial taxonomies for the basic assembly processes, including:

- Material Handling Equipment Taxonomy: Material handling equipment (MHE) is used for the movement and storage of material within a facility or at a site. MHE can be classified into the following five major categories: Transport, Positioning, Unit Load Formation, Storage and Identification and Control Equipment. This knowledge source enables us to categorize constituent equipment artifact's relating to and/or involved within the handling and transportation of materials within assembly plants.
- Product Assembly Process Taxonomy: This taxonomy includes three major subcategories; namely, Pre-Assembly, Components Assembly and Post-Assembly processes. When considering G2G processes, we are specifically interested in the components assembly aspect of the product assembly process taxonomy.
- Joining Process Taxonomy: As an example of measuring energy performance metrics for processes involving the use of complex equipment we utilize this taxonomy as it provides an additional level of granularity for constituent sub-processes specific to the Joining Process aspect of product assembly.
- Automobile Manufacturing Taxonomy: For the purpose of establishing an information integration model for process-to-energy (P2E) reporting. The automobile manufacturing taxonomy enables us to link processes (such as the joining and product assembly process) to actual automobile parts being manufactured within the assembly process.

Establishing the taxonomies of the different processes enables designing an information service framework that could link energy calculations and measurements as services to gate-to-gate process-to-energy reporting within automobile assembly. The information models will provide the basis to systematically organize and to evaluate performance metrics developed by the industry groups and researchers.

Chin – Sheng Chen

1. To assess sustainable manufacturing what parameters should be measured to compute resource efficiency in terms of energy, material, and water?
   a. Many researchers have argued that manufacturing sustainability (MS) assessment should take place at the resource component level and by each operation mode. A typical machine operates in three modes: machining (the machine is fully engaged in metal removal and machining), idling (the machine tool is in standby with its peripheral units turned on), and traversing (the machine's axes and spindle are in motion but no material is being removed). Typical machine components that consume energy, material, and water include axis motor, spindle motor, coolant pump, air compressor, chip conveyer, automatic tool changer, tool magazine, hydraulic pump, computer fan, and exhaust fan, among many others.
   b. Energy consumption parameters commonly used for machining are cutting force, load, material removal rate, the depth of cut, feed, surface speed, machining time, idling time, traverse time, and tool change time.
   c. Material parameters include raw material use, raw material consumption (chip), and raw material consumption (scrap). Additional material parameters are cutting tool consumptions, engineering tooling consumption (e.g., molds and dies), device consumption (e.g., jigs, fixtures, baskets, and pallet), and lubricant consumption.
   d. Water used for machining is in the form of coolant or cutting fluid. Coolant consumption is a function of cutting fluid rate and coolant usage time.

2. What are the key factors that contribute to uncertainty in sustainable manufacturing? How can we prioritize these and what measurement techniques can be applied?
   a. There are at least three approaches to assessing manufacturing sustainability: direct measurement, computation, and use of nominal data.
   b. Direct measurement would be ideal as its uncertainty reduces to calibration of the measurement tool/meter used. Though the effort of direct measurement could be largely automated to improve the efficiency of data collection, data collection however, cannot happen until manufacturing actually occurs.
   c. When it comes to computation using metrics (quantitative models or equations), many factors could contribute to the uncertainty of manufacturing sustainability, such as variation in material property, operational parameter setting, machine model and maker, rigidity of work-piece setup, temperature, or even humidity. The computation approach has its challenges, as a separate metric (and parameter setting) may be needed for possibly each material type, each unit process type, and each machine model/maker, consisting of different motors, drivers, cutting tools, and holding devices.
   d. Use of nominal data could face challenges similar to the computation approach, because it would require a tremendous amount of coordinated efforts to build a data base in order to support for a range of materials and unit processes types, using various machine/equipment resources.
   e. Computation has been a popular focus of many academic research efforts as well as SM projects, for it could be more scientific and productive. Direct measurement

via tools such as the MTConnect[9] could be useful for collecting and establishing a sustainability reference database, in parallel to collecting real production data from industry partners.

3. How would a material model that supports sustainability decision be formulated?
   A material model of sustainability should consider a bill of materials (BOM) for the product components, but also raw materials, engineering tooling, and tooling materials. Since tooling is used for a unit process and tooling may also require its own tooling, thus such a BOM structure could have multiple layers with linkages pointing a material to a component or a tool, which in turn points to a unit process. Jigs, fixtures, baskets, pallets, molds and dies are typical engineering tooling.

4. How can sustainability data for a manufacturing part or assembly be aggregated to enable sustainability analysis?
   a. Typical sustainability data for a manufactured part or assembly can be viewed as a table of numerical values. Each entry is a measurement, computation, or nominal value for a unit manufacturing process under a sustainability indicator.
   b. To enable sustainability analysis, a normalization method should be used to transform these values to address the nature of difference in the processing technology and machine type as classified by each unit process type definition. Linear scale transformation and vector normalization are two commonly used methods.
   c. For aggregation, a weighting method should be applied to evaluate relative importance of each sustainability indicator. Eigenvector method, weighted least square method and entropy method are often considered for this purpose.
   d. Similar concepts of normalization and aggregation could be applied to assembly products, following the component/material structure defined in the BOM model.

5. What are the information modeling concepts that are unique to sustainability characterization and optimization?
   a. For sustainability characterization, the information modeling concept should capture intermediate material information (of shape, size, form feature, and surface property, etc.) in each step of a unit manufacturing process, and energy (as well as other consumables such as tooling, lubricants, gases and coolants) consumption profile for each operation mode of each unit process type and each machine (equipment) model/maker. It should profile emissions in the same manner. The consumption and emission profile should be captured at the machine/equipment component level as it is where energy is consumed and emissions occur.
   b. For sustainability optimization, the information model needs to capture alternative process technologies and production plans, with alternative routings, resources and operational parameters. Sustainability optimization could be exercised through alternative product designs as well.

[9] MTConnect is a manufacturing industry standard to facilitate the organized retrieval of process information from numerically controlled machine tools.

6. What are the characteristics of an effective manufacturing-focused sustainability assessment methodology?
   a. An effective methodology needs to meet the general criteria of desirability, operationability, and practicability.
   b. It is desirable to assess manufacturing sustainability of a product design via its manufacturing process or production plan defined for a specific plant location, if the manufacturing industry is the target user of the MS assessment methodology.
   c. It should have sufficient detail (of steps and instructions) for each assessment activity to be operation-able without relying on a consultant/expert.
   d. It should be practical enough such that a corporate user can readily apply it to one of its corporate business units for a specific product (group) in a life-cycle phase, after selecting SM indicators, reference data set, and assessment techniques.
   e. It should provide the MS functions of definition, assessment, analysis, improvement and control, such that a corporate and factory-level user can engage in the continuous improvement process of assessing and optimizing its corporate-wide and factory/site specific manufacturing sustainability.

7. What are requirements and challenges for a shared research testbed and what types of things could be tested there?
   a. Potential customers:
      i. Developers of metrics, models, techniques, methods, and tools.
      ii. Academic and governmental R&D partners.
      iii. Commercial hardware and software developers.
      iv. Manufacturing partners of discrete part and products.
      v. Machine and equipment makers.
   b. Types of things to be tested (use of the testbed):
      i. For developers, R&D partners, and commercial developers
         1. Validate MS measurement/assessment metrics, techniques, models, methods, and tools for standards compliance.
         2. Characterize their performance with theoretical and industrial data.
         3. Assess their application in industry settings.
      ii. For manufacturing partners:
         1. Validate their manufacturing process and production plans for conformance to standards.
         2. Benchmark manufacturing sustainability of their manufacturing process and production plans.
         3. Perform MS assessment.
      iii. For machine and equipment makers
         1. Characterize input efficiency (material, energy and water consumption) at the machine/equipment level.
         2. Characterize input efficiency (material, energy and water) at the machine/equipment component level.
   c. Testbed requirements
      i. It will support rapid configuration for modeling and assessing manufacturing routings and production plans for manufactured products within the domain of interest.

ii. It will be populated with assessment tools, methods, models, techniques, best practices and reference data sets, in support for a range of sustainability indicators and unit manufacturing processes required for manufacturing sustainability assessment of manufactured products within the scope.
iii. It will have an aggregation feature that enables integration of individual assessment data at the unit process level, for product-level sustainability assessment and analysis.
iv. It will support multiple assessment approaches (e.g., direct measurement, computation, and use of nominal data).

d. Challenges
   i. Identification of an industrial product with a production plan that can utilize assessment metrics, tools, methods and techniques developed by projects in the SM program.
   ii. Establishment of a theoretical and industrial sustainability reference database in the tested for benchmarking and base-lining.
   iii. Collection of sufficient data for a range of resources and unit process types to support experiments and validation of MS metrics, techniques, methods, and tools.
   iv. Collection of sufficient real production data for benchmarking and base-lining and to support validation and characterization of the MS metrics, techniques, methods, and tools.
   v. Experiments to be designed and conducted in the testbed for validating and characterizing the performance of intended MS metrics, techniques, methods, and tools.

Appendix B: Breakout Group Reports

The two breakout groups were organized by thrust area. A report from each group follows.

Methodology Thrust – Breakout Report
November 13, 2012

Facilitators: KC Morris, Paul Witherell, and Kevin Lyons

QUESTION 1: To assess sustainable manufacturing what parameters should be measured to compute resource efficiency in terms of energy, material, and water?

This question addresses what factors should be measured and how to establish baseline and boundary conditions for measuring manufacturing resources. These serve as a baseline in assessing the trade-offs of the system as it is optimized. Boundary conditions reflect sensitivity issues in the nexus of energy, material, and water modeling and optimization. For example, are there thresholds for any one of the three resources beyond which the demand on one of the others is dramatically impacted? Finally, the question addresses models or modeling approaches that use actual measurements to improve the overall efficiency of the system.

- The discussion of what parameters should be measured quickly moved to how to normalize measures (as discussed above). Metrics would depend on the point of view of the person doing the measurement. Optimizations can be done for whatever the metric is--when you decide what to measure, you are also deciding what you will optimize.
- The idea of developing a set of benchmarks as a basis for measurement was discussed. The benchmarks would define a baseline against which sustainable improvement could be measured. Benchmarks would need to be organized in some way such as product class, energy use, process efficiency, or activity.
- A dichotomy was identified as follows:
  - completeness of measurement--such as complete accounting of energy and material for a factory producing an average per unit of product
  - measuring a single variable and how it varies in the context of controlled parameters. It was argued that this latter approach was a better approach for sustainability improvement.
- There seemed to be agreement that a process taxonomy including terminology definitions would be extremely useful. Standard definitions for processes would enable clearer definition of metrics. Apparently some work has been started on that from NRC.

- The discussion centered on material efficiency – initial discussion was on unit mass. However, when you compare different processes this may not make much sense as additive manufacturing may be completely different from powder injection molding.
- The notion of dollar value was discussed as a measure for normalizing material usage
- Alternative materials may lead to design changes and hence one should capture these changes in material efficiency

- The variations on processes leads to the need for defining process taxonomy
- The DIN and NRC Classifications were touched upon
- Discussion touched on what is the definition of "Waste."
- The group as a whole felt that we need to define material efficiency on a process basis

QUESTION 2: What are the key factors that contribute to uncertainty in sustainable manufacturing? How can we prioritize these and what measurement techniques can be applied?

Measurement techniques might address the level of granularity of measurements, frequency of measurement, and level of uncertainty in the data. First we need fundamental research to develop and demonstrate such techniques before proposing standards for these measurements (which we do intend to do.) Such techniques should also address the concern of how uncertainties and errors associated with sustainable manufacturing indicators at unit process through enterprise level are best handled. Techniques are also needed to address the flow of information from the supply chain and to validate the data reliability and provide data traceability. In addition, this question may address the integration of Lifecycle Inventory (LCI) data, which represent industry averages, with more local measurements (such as plant-specific).

- As what needs to be measured was not clear very little discussion was there on uncertainty
- Uncertainty in measurement seems to be heightened by the fact that in a real scenario there will always be some "missing" or unmeasured data. Any measurement approach will need a way to account for missing data or input errors. There was also a discussion of the reliability of measurements as an accurate representation over time since any single measurement is really only a reflection of the circumstances in which it was taken. Any model developed to account for these factors, providing theoretical values obtained via computation, must itself be evaluated for quality.

QUESTION 3: How would a material model that supports sustainability decisions be formulated?

Given that material information is pervasive in product design and manufacturing, it provides a solid foundation on which to establish the metrics for sustainability. At the same time it provides a link from the virtual world of design to the physical world. This question addresses what a model of material information would look like to support sustainable design choices. In particular, the properties that best capture the information needed to make sustainable material choices need to be identified and organized in a systematic way, perhaps being characterized across material types. Material information in product development is quite broad. The scope of a model to support sustainable design and manufacture would be unique yet would need to interoperate with the wide range of material models that already exist. Approaches for presenting the sustainability information about materials also need to be explored.

- There was significant discussion of the role of PCRs and whether an equivalent method could be defined and used for process. The sense was that process was of such a different nature and that it was so tightly coupled with other factors that there would be no equivalent.

- There was reference to quality standards for products and relating them to aggregating measurements both in a deterministic and non-deterministic sense
- The EPD and PCR (product category rules) were offered as possible ways
- Different views (services) may help in aggregating measurements and building metrics
- Material model should
    - account for decision space for alternatives,
    - an assessment metric should be expressed as a function of control variables to represent trade-offs,
    - factor in "costs" associated with the material from other life-cycle phases (e.g. material sourcing and material use) along with traceability to the other phase
    - to fit to SPAF structure should include a library of metrics, association to process model, expressions of material consumption.

QUESTION 4: How can sustainability data for a manufactured part or assembly be aggregated to enable sustainability analysis?

Energy use, for example, is a primary factor influencing sustainability but energy use is difficult to gauge in a complex or even relatively simple manufactured good. The production includes the energy used by the facility, energy used by different machines and processes, energy used in producing and transporting component parts. All of these measures contribute to the assessment of energy use for a particular item and yet standards for how that use is apportioned and totaled do not exist. When we expand the scope of sustainability indicators beyond energy use, the order of complexity of this analysis problem grows dramatically. This challenge is compounded by the fact that different processes may have characteristics unique to them. What are these characteristics, how can they be normalized? Furthermore, the accuracy and integrity of measurements is difficult to verify. Techniques are also needed to address the flow of information from the supply chain and to validate the reliability of and provide traceability.

- aggregation of metrics requires a common denominator in order to aggregate up
- in aggregation care should be taken to avoid double accounting
- regression analysis could be applied to account for missing detailed measures, how to aggregate shared resources, create analytical formulation and find consumptions averages per machine

From both sessions:

- Both groups discussed how metrics could be normalized and agreed that metrics could not be compared without normalization. Different ideas that emerged were measurements in terms of mass efficiency, waste, term of use, measures per part, measures per value added, GHG. The only agreement that seemed to emerge on this topic was that no single normalization approach would be appropriate but that normalization would need to be defined in terms of other sustainability goals.

- There also seemed to be agreement that no single factor could stand in isolation as a metric but that metrics need to be defined in functional terms which would factor in trade-offs.

SOME FINAL THOUGHTS

1. Each research group may want to answer the questions and send them back to their TPOCs to initiate a dialogue and working document..
2. It is decided to select one or two products (which will serve to focus the group's attention) and try to generate answers to all the questions raised over the next few months

Infrastructure Thrust – Breakout Report

Facilitators: Frank Riddick and Gordon Shao
Scribe: Tina Lee

Question 1) ***What are the information modeling concepts that are unique to sustainability characterization and optimization?***

Discussion

- Many information models were mentioned. Can one information model cover all of the different modeling requirements?
  - It was suggested that it would be better if there could be one model.
  - If there are different models, it should be possible to translate from one model to another.
- Although several of the SM and collaborator presentations showed an information model of a manufacturing process to be used as the basis for analysis, most of the models seemed to be consistent with a process-based LCA modeling structure.
- To what level of granularity should equipment used in manufacturing processes be modeled (machine vs. component)? Does the answer depend on what kind of analysis is going to be performed?
- The program should consider supporting Fate and Transport modeling for manufacturing facilities.

Question 2) ***What are the characteristics of an effective manufacturing-focused sustainability assessment methodology?***

Discussion

- The modeling and representation of manufacturing processes may differ depending on the phase of manufacturing that is being modeled/assessed.
  - Product design
  - Process design
  - Manufacturing system/production design
  - Production operations
- It might be better to first focus on analyzing one fixed process plan for a product and then move on to analyzing a processes plan with many alternatives.
- Different advanced decision making techniques (such as AHP) should be explored but their feasibility should be weighed against what manufacturing end users will accept.
- The methodology should be general. When applied to different case studies, different weights may be used to compute the metrics supported by the methodology.
- It was suggested that the methodology support a holistic sustainable manufacturing analysis (note: the focus of the SM program is economic and environmental analysis of gate-to-gate manufacturing processes)

- The methodology should support optimization in support of site selection studies.

Question 3) ***What are requirements and challenges for a shared research testbed and what types of things could be tested there?***

Discussion

- One real product scenario should be selected to be the basis for all of the SM projects research and demonstrations.
- The testbed and testing requirements should come from
    - All SM projects
    - Industry partners
    - SW application vendors

  (note: this is the approach that is being undertaken by the testbed project)
- The testbed should be designed to use a virtual representation of a manufacturing facility and its processes.
- It is ok if some of the data collected is be of differing quality (measured vs. computed) as long as it is recognized that this will affect the uncertainty of any analysis results.
- It would be nice if the testbed would provide the data collected from various studies so that SMEs could come in and use it as a basis for analyzing their operations.
- The testbed should not be general but designed to support real manufacturing case studies.

Appendix C: Research Teams and Abstracts of Presentations

Workshop Presenters
NIST Team: Sudarsan Rachuri, KC Morris, Kevin W. Lyons, Shaw C. Feng, Gordon Shao, Swee Leong

Non-NIST Teams

1. **Prof. David Dornfeld and Dr. Margot Hutchins, UC Berkeley**

Enabling Standards Development for Sustainability in Manufacturing: The research work will focus on sustainability metrics for manufacturability (including design specifications for products, processes, and systems) and will closely work with projects towards developing the methodology for sustainability characterization for unit manufacturing processes and integration framework for aggregating metrics and modeling sustainability. This cooperative research agreement will help to foster a strategic relationship with a leading university for standards development.

2. **Prof. Soundar Kumara, Prof. Christopher Saldhana, and Qais Al-Khazraji, The Pennsylvania State University**

Design, Development and Implementation of Material Information Models for Sustainable Manufacturing: Development of a high-level unified model for organizing material information from these various sources, incorporating sustainability metrics for those materials including uncertainty quantification. The model will provide an accurate framework for representing the entire lifecycle of material information, from raw material processing to end of use, maintenance and disposal. This work will address information models for materials and is critical for ASTM E60 related work.

3. **Prof. Alex Brodsky, and Prof. Daniel Menasce, George Mason University**

Process Analytics Language (PAL) for Sustainable Manufacturing: Modeling, Analysis and Decision Optimization: Create and catalog formal manufacturing process specifications in terms of (1) sub-processes, their coordination and flow of resources, and (2) mathematical specification of process metrics and constraints expressed in terms of parameters and control variables. This work is related to integration infrastructure for sustainable manufacturing thrust.

4. **Prof. Utpal Roy, Syracuse University**

Information Models for Material and Material Processing for Product Lifecycle for Sustainable Manufacturing: The three major tasks are related to the information processing for material and process representations and analyses, and the development of necessary case studies to illustrate the proposed methodologies. This work is an extension of ongoing work to address measurement science and information models for materials and is critical for ASTM E60 work.

5. **Prof. Kincho Law, Stanford University**

Supply Chain Characterization for Sustainable Manufacturing: This proposed cooperative project aims to investigate information infrastructure and methodologies that support (1) the characterization of sustainable product assembly and manufacturing processes, and (2) the development of measurement metrics for sustainable product lifecycle assessment. This work will develop a relationship with Supply Chain Council (SCC) and Automotive Industry Action Group (AIAG) to extend the Supply Chain Operations Reference (SCOR®) model for sustainable manufacturing.

6. Prof. Satyandra Gupta, UMD (did not attend)

Environmental Impact Analysis for Sustainable Manufacturing: A Framework and Injection Molding Case Study: The research work will focus on characterizing unit manufacturing process for sustainability. Work will be done in collaboration with the project on Sustainability Characterization for Unit Manufacturing Processes to develop the methodology for sustainability characterization. This work will contribute to the ASTM E60 WK35705 effort on New Guide for Sustainability Improvement of Manufacturing Processes.

7. Prof. Sanjay Jain, GWU

Sustainable Manufacturing Maturity Model: This cooperative project will contribute a maturity model that gauges the current sustainability performance of a factory possibly against a set of defined levels and provides the next level as target. Similar models for other related areas would be reviewed. The options of discrete maturity levels, continuous scale of quantitative metrics, and a hybrid of the two for assessing maturity will be considered and appropriate option or a combination selected. The developed model will be evaluated through application to a case study.

8. Dr. Rita Schenk, American Center for LCA

State of the art and measurement science need for product declaration based on Product Category Rules (PCRs): The work includes, a review the current U.S. industry adoption of PCRs for EPDs and what are the implementation issues. Specifically, it will address the issues for SMEs. Analyze the industry reality in the U.S. and in the global supply chain. The work will also define the industry requirements for U.S. EPD program and assess the measurement science issues and also practical issues in performing the LCA for EPDs and for Type I environmental labeling, Type II self-declared environmental claims, and Type III environmental declaration.

9. Prof. Chen, Cyber Manufacturing Inc.

Enabling Infrastructure and Technologies Support for Sustainable Manufacturing: The Contractor shall focus on the development of enabling methods, tools, manufacturing sustainability assessment methodology, and demonstration system capable of analyzing the manufacturing requirements and sustainability performance of a simple assembly in a manufacturing cell with a given production plans, including but not limited to, the identification and definition of relevant product, process, resource, and related sustainability information.

Appendix D: Workshop Agenda

November 13, 2012

Time	Title	Speaker
8:30-8:45	Welcome Remarks	Shyam Sunder
8:45-9:15	Overview SM Program and the meeting goals	Sudarsan Rachuri
9:15-10:15	Projects Overview and Research Collaborations	Project Leads (12 minutes each)
10:15-10:30	BREAK	
10:30-12:10	UCB, PSU, Syracuse, Stanford, UMD	20 minutes each–Thrust One
12:10-1:10	Lunch	
1:10-2:30	GMU, GWU, Cyber Manufacturing, ACLA	20 minutes each –Thrust Two
2:30-2:45	Break	
2:45-5:00	Breakout Discussion	2 Breakouts based on thrusts
2:45-3:45	Methodology Thrust	UCB, PSU, Syracuse, Stanford
2:45-3:45	Infrastructure Thrust	GMU, GWU, Cyber Manufacturing, ACLA
4:00-5:00	Methodology Thrust	GMU, GWU, Cyber Manufacturing, ACLA
4:00-5:00	Infrastructure Thrust	UCB, PSU, Syracuse, Stanford

November 14, 2012

Time	Title	Speaker
8:30-9:30	Breakout Discussion – Group presentations	Group Representatives
9:30-12:00	Success factors, Deliverables, milestones, standards - Roadmapping	NIST PIs, CRAs, Contractors
10:30-10:40	BREAK	
12:00-1:00	Lunch	
1:00-2:00	Future Steps/Plan for Industry Workshop/ Visits …	Sudarsan Rachuri (Moderator)
2:00	Adjourn	