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SUSTAINABLE MANUFACTURING INDICATOR REPOSITORY

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ABSTRACT
Sustainable manufacturing promotes manufacturing processes that minimize environmental and social impacts while maintaining economic benefits. To achieve this, manufacturers seek metrics and measurement methods to enable them to track the progress and manage their manufacturing processes and product designs. A number of indicator sets have been devised to analyze and score sustainable manufacturing; however, presence of many indicator sets has created difficulty in selecting the appropriate set. This paper presents a sustainability indicator repository, called Sustainable Manufacturing Indicator Repository (SMIR), an integration and extension of thirteen popular sustainability indicator sets. From an extensive review of publicly available indicator sets, the SMIR is based on five dimensions of sustainability: environmental stewardship, economic growth, social well-being, technological advancement, and performance management. The purpose of the SMIR is to provide an organized set of centralized, Web-based, open, and neutral indicators that can be accessible by small and medium size manufacturing enterprises. The SMIR can be an application as well as educational tool for manufacturers by providing them with necessary information on in-process and off-line sustainability measures.

Keywords: Indicator repository; sustainability indicators; sustainability measurement; sustainable manufacturing.

1 INTRODUCTION
Manufacturing enterprises in the United States and around the world are facing a myriad of challenges to stay competitive in the market place. These challenges are spawned by the need to broaden the expectation beyond the profit of shareholders to sustainability for all the stakeholders, including customers, suppliers, and the rest of the society. Sustainability, which has recently come to the forefront, encourages manufacturers to conduct operations in ways that protect the natural environment, human health, and societal interests. Other pressures, such as government regulations, limits to resource availability, and ethical responsibility, have only exacerbated this need to become sustainable. This in turn has caused a reaction by the manufacturing industry to not only change the way they operate but also reconsider the way they measure success. In view of this, it is important to examine exactly what sustainable manufacturing is. According to the definition from the United States Department of Commerce [1], sustainable

manufacturing assumes three dimensions for sustainability (i.e., economic, environmental, and social). Furthermore, sustainability needs to be assessed throughout the life-cycle of a product. The requirements embedded in the definition of sustainable manufacturing cover a breadth of what should be analyzed in regards to sustainability. With such a wide application field, the result has thus been the development of a number of measures and metrics by means of indicators, indicator sets, and indices for analyzing sustainable manufacturing. With a great number of performance indicators, manufacturing enterprises have been challenged to decide which indicators they should choose. Challenges are also on how they should interpret these indicators in making their processes and products sustainable.

The purpose of this paper is to present the Sustainable Manufacturing Indicator Repository (SMIR). The SMIR will help manufacturers by compiling and organizing many publicly available and used indicators, indicator sets, and indices. These indicators span a variety of stages in a product lifecycle. Each indicator has a definition, unique identifier, unit of measure, and references. For the intent of this repository, the available indicator sets have been communalized and enhanced to be applicable to the manufacturing industry thus removing added complexity to manufacturers in search of process-level sustainability indicators. Furthermore, the presented SMIR is a part of a sustainable manufacturing measurement infrastructure, which will in its entirety manage multi-dimensional sustainability indicators for the evaluation of products and processes in regards to sustainability [7].

The remainder of this paper will discuss a background on measuring sustainability by detailing existing indicator sets, the basic functions of the in-process sustainability measurement infrastructure, how the SMIR fits within this framework, and a detailed account of the purpose and structure of the SMIR.

2 BACKGROUND

2.1 Indicator Sets and Indices

An indicator is a single parameter used to measure the condition of an aspect in a system. In this case, it measures the condition of an aspect in sustainability, such as CO_2 emission or energy use. In decision making, indicators would be used in detailed-level management because they provide a partial view of sustainability and are thus easily controlled. For example, water use is an important indicator for environmental sustainability and can be easily controlled via simple decision making and management, but since water use only represents a very small portion of the total idea of sustainability, it should not be used to make high or organizational level decisions regarding sustainability. For such decisions and evaluation, indicator sets and/or indices are normally useful. An indicator set, as the name implies, is a set of indicators that when used together will comprise a more holistic view of sustainability. Combining indicators from the environmental, economic, and social dimensions and evaluating those indicators together will measure the sustainability on a much larger scale than individual indicators and, if interpretable, will create focus areas for improvement in regards to sustainability. Interpretability with indicator sets is, however, a key issue because the complexity of the interrelationships of indicators causes a number of contrary conclusions about the level of sustainability and what can be done to improve it [12], [19]. In contrast to indicator sets, indices provide a more straightforward conclusion on the level of sustainability because they rely on mathematical methods to aggregate many indicators into a single score. With a single score, a sustainability level can be set and used as a metric for performance, but still in regards to how to improve the sustainability contrary opinions can be drawn because of possible different interpretations of the indicators at a low level. Such difficulties with decision making have led to the introduction of a number of indicators, sets, and indices to attempt to match the varying level of evaluation. With current indicators, sets, and indices, sustainability is measured at different levels from low levels (process or product), high levels (organization or company), to macro-levels (region or nation) [13].

In understanding these challenges and for construction of the SMIR, thirteen publicly available indicator sets and indices were used. They are Global Report Initiative (GRI) [9], [18], Dow Jones Sustainability Indexes (DJSI) [16], 2005 Environmental Sustainability Indicators (ESI) [4], 2006 Environment Performance Index (EPI) [3], United Nations Committee on Sustainable Development (UNCSD) Indicators of Sustainable Development (ISD) [20], Organisation for Economic Cooperation and Development (OECD) Core Environmental Indicators (CEI) [14], Ford Product Sustainability Index (PSI) [17], GM Metrics for Sustainable Manufacturing [2], International Organization for Standardization (ISO) 14031 environmental performance evaluation [10], Wal-mart Sustainable Product Index (SPI) [21], Environmental Pressure Indicators (EPI-EU) for European Union [5], Japan National Institute of Science and Technology Policy (NISTEP) [11], and European Environmental Agency Core Set of Indicators (EEA-CSI) [6].

The focus of the publicly available sets and indices vary according to the scale of measure for sustainability. Many of the sets and indices focus on the sustainable development or macro-aspect of sustainability, where an entire region or country is evaluated (see ESI, EPI, EEA-CSI, EPI-EU, OECD CEI, UNCSD-ISD). The remaining sets and indices focus more on the manufacturing process-level of sustainability per organizational or process/product performance (see DJSI, Ford PSI, GM, GRI, ISO 14031, NISTEP, and Wal-mart SPI).

In comparison and contrast to all the sets and indices, there are a number of commonalities and dilemmas that arise, especially in the development of a standard indicator repository. The most striking commonality is in the primary focus on the environmental aspect of sustainability. All sets and indices with the exception of the NISTEP, which focuses primarily on the social dimension per technology advancement, contain indicators or have a focus on the environmental aspect. Beyond the focus on the environmental dimension, the reviewed indices and sets above all provide some means for decision making whether through simple aggregation and evaluation or through point-by-point consideration of indicators. This dilemma creates a need for standard criteria for decision making in regards to sustainability. Moreover, because of the varying levels of integration and assessment for decision making, decision criteria in a standard must have flexibility for use and implementation. The key in this evaluation and in the development of the SMIR was how a standard set of indicators can be formed that will collectively assess all dimensions of sustainability for manufacturing, while maintaining the needed flexibility for companies, organizations, and manufacturers in their assessment of their sustainability performance. Thus, the SMIR described in this paper attempts to solve this problem through its structure, setup, and application. Furthermore, the placement within an in-process sustainable manufacturing measurement infrastructure enhances its usefulness in the evaluation and assessment of sustainability.

2.2 NIST Sustainable Measurement Infrastructure

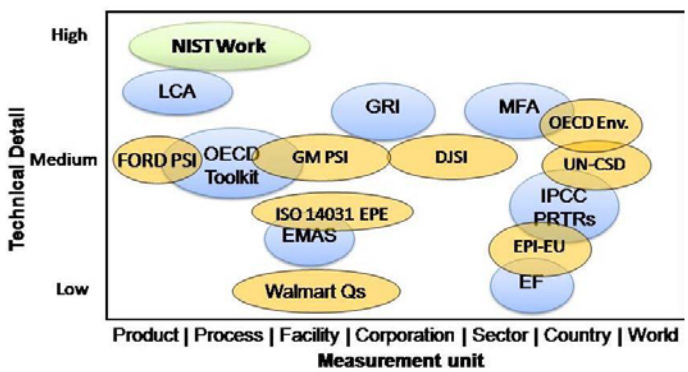

Figure 1. Technical detail and measurement level comparison of in-process measurement infrastructure and other measurement systems [15]

The sustainable measurement infrastructure being developed at NIST will provide manufacturers with a novel means for evaluating their processes and products in regards to sustainability. The infrastructure is also applying sustainable measurement and assessment to a degree that has yet to be seen by current measurement means (See Figure 1). NIST's work is primarily focused on the manufacturing process-level assessment of sustainability, which promotes great details about the information needed and the decisions that can be made to promote sustainable manufacturing. Furthermore, with such a process-level assessment, a bottom-up approach can be taken that will successfully aggregate the proposed assessments to not only a process- or product-level but to a company/organization and even regional level. The key to achieving such flexibility in sustainable assessment and measure is in the Sustainability Performance Management (SPM) component of the in-process infrastructure (See Figure 2). The SPM within the measurement infrastructure is the central entity for the measurement infrastructure and performs a variety of functions including:

- Managing a multi-dimensional indicator set stored in the SMIR by providing several functions, such as requirements for updating the indicator set, versioning control, and ensuring consistency with measurement process guidelines and the reporting function
- Providing requirements and guidelines for calculating and formulating sustainability scores and assessments through the management of the Sustainability Measurement Process Guidelines (SMPG) component
- Generating internal and external reports, based on the functions within the Sustainability Performance Analysis, Evaluation, and Reporting (SPAER) component for which is heavily dependent on the users assessment and evaluation desires

While the overall structure and detailed functions of the sustainable measure infrastructure and its components are intended to help in the understanding of the purpose and function of the developed indicator repository, they are beyond the scope of this paper. For further information concerning the overall sustainable measure infrastructure being developed at NIST consult [8].

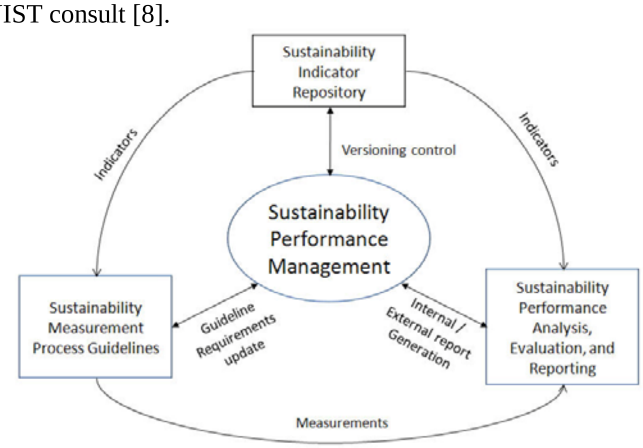

Figure 2. In-process sustainable measurement infrastructure structure and information flow [8]

3 Sustainability Indicator Categorization

The SMIR contains sector-specific multi-dimensional indicators developed from existing indicator sets and indices. Organization of the indicators within the repository was done according to a structure that this paper describes. It incorporates the multi-dimensionality of sustainability by including the three main dimensions of sustainability, economic growth, environmental stewardship, and social well-being, along with two additional dimensions, technological advancement and performance management (See Figure 3). Indicators from existing indicator sets (See Background section) were reviewed and categorized by the structure. The SMIR is purposed for sustainable manufacturing and thus requires process-level indicators. This would seemingly eliminate regional and national sustainable development measurement systems from consideration; however, a review of such systems indicators of similar function and meaning were included within the indicator repository and adapted toward applicability in sustainable manufacturing.

The developed SMIR structure is based on the three main dimensions of sustainability-environmental stewardship, economic growth, and social well-being, as well as two additional dimensions-technological advancement and performance management. The basis of the SMIR structure allows users to easily and efficiently search indicators by selecting from the root of sustainability branches denoted by the determined dimensions and their given aspects. The leaves of the structure likewise become the actual indicators. Only the hierarchical structure is discussed in this session.

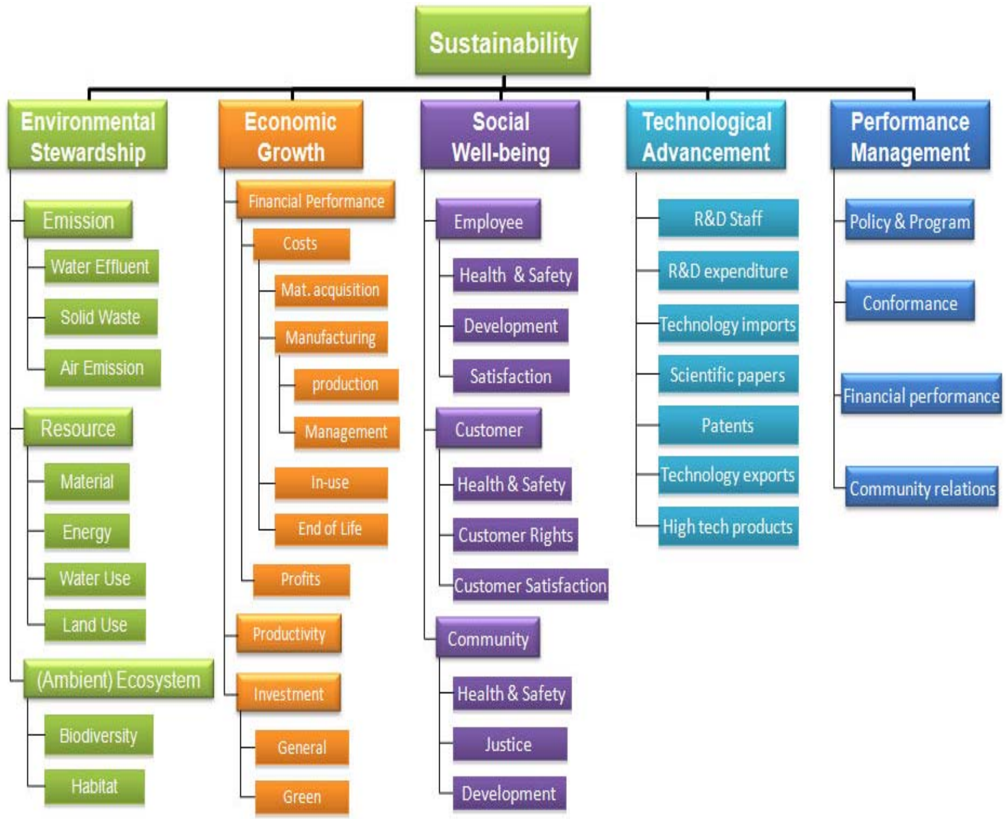

Figure 3. Indicator categorization structure containing three main dimensions of sustainability, economic, environmental, and social; and two additional dimensions, technological advancement and performance management

For environmental stewardship, a wide range of indicators were categorized per organizational and/or process/product impacts from emissions, resource use/depletion, and on the ambient ecosystem. Three subcategories are as follows:

- Emissions include discharge (solid, gaseous, or liquid) indicators for which an organization or process releases during the production of a product or service, as well as the discharge of the product or service during its life. These indicators are basic in determining the environmental impacts for production and use of products.
- Resource category includes any indicator which measures the material, energy, water, and/or land used by an organization or process in the production and use of a product. The resource category and its indicators will collectively measure the preservation or depletion of given resources (materials, energy, water, and land) for the manufacture and use of a product.
- Ecosystem concerns indicators which show impacts on the surrounding biodiversity and habitat of an organization. Biodiversity and habitat management and conservation are important in maintaining the flora and fauna species and overall ecosystem within an environment.

For economic growth, indicators measure the economic performance, the productivity, and the investments from an organization and its process and products. Three subcategories are as follows:

- Basic financial performance indicators include measures for profits and operational costs. Costs are accrued from material acquisition, manufacturing, and end-of-service-life product treatment. These basic indicators are commonly used by many companies and manufacturers to establish cost and profit guidelines and decisions. Costs of manufacturing include production and management. Production costs include energy, tooling, labor, waste management, packaging, delivery, and storage. Management costs include supply chain management, environmental protection programs and projects, brand management, risk and crisis management, customer relationships, and employee benefits. Product use costs, such as fuel and taxation, are a part of product lifecycle cost. End of life costs include recycling, reuse, and remanufacturing costs to reduce waste and save natural resources.

- Productivity indicators are an essential part for any organization as they measure the overall financial efficiency of an organization and its processes. The basic and most commonly used measures for productivity concern personnel and labor efficiency and are, thus, a major indicator for this aspect.
- An organization's investments and how they manage those investments is another key aspect of the economic growth for a manufacturing enterprise. Investments quite often establish the growth of a product and/or company and must be used to measure the overall financial growth and sustainability of an organization. For the purposes of sustainable growth, not only are general investments that promote financial and social growth of the organization included, but also green investments that promote environmentally friendly investments, which aim to mitigate environmental impacts.

Social well-being indicators are those for which an organization, process, or product has a societal impact through general health and safety practices, development management, and human rights. In particular, a focus on each of these societal impacts is placed with employees, customers, and the community. Three subcategories are as follows:

- Employee indicators cover the overall health and safety of employees while at work, their skill development per given programs, and their satisfaction within an organization. Such indicators are essential to sustainability as they consider the rights of workers and indirectly their effectiveness in regards to quality and performance.
- Customer indicators like that of employees cover the health and safety impacts from manufacturing and product use, satisfaction from operations and products, and the conformance and inclusion of specific rights for customers. The determined aspects with these customer indicators directly reflect the ability of the organization to meet the demand of customers per sustainable operation and product use.
- Community indicators are directly related to an organization's actions per its philanthropy, social amenities, development, and human rights works. All such works maintain the organization's standing amongst the surrounding community and its overall relation with the community without which operation would be difficult if not impossible.

The performance management indicators collectively include all three main dimensions of sustainability, but do not directly measure these dimensions. Four subcategories are as follows:

- Policy and program performance indicators directly measure the management of objectives and policies of an organization for sustainable production and manufacturing. Performance indicators such as these will begin the benchmarking process for an organization and the development of metrics for sustainability per the adherence to specific programs and policies put in place by the organization.
- Conformance indicators evaluate the ability of an organization to meet or exceed general and sector-specific guidelines for manufacturing processes and products.
- Financial performance measures the economic performance of an organization in regards to environmental expenditures and investments, along with the generated savings from such environmentally related projects.
- Community involvement concerns the openness of an organization for community education and development for sustainable development.

The technological advancement measures the personnel makeup of an organization and indirectly contributes to all three main dimensions of sustainability. The focus of this dimension being the ability for the organization to promote technological advancement for society through education and research & development and in the contributions made through patents and publications. No subcategory in technology advancement.

- R&D staff considers the experience of personnel within the R&D departments of an organization or company for the benefit of innovation in product and process development.
- R&D expenditure concerns the monetary and time investments for R&D projects within an organization.
- Technology imports are the technologies or products imported from out of the country of residence for an organization and specifically establish a technology level for an organization based on the availability to certain technologies and products.
- Scientific papers published by an organization are a benchmark in the contributions an organization can make to the scientific community to further technological developments.
- Patents, as with scientific papers, establish the organizations level in innovative concepts and contributions per new technologies and products.
- Technology exports are opposite to imports in that exports provide a global measure of the use of certain products and technologies manufactured by an organization in other countries and regions.
- High tech products are the licenses sold for improving processes and products. They relate to technology exports as the contribution of an organization to technological advancement and development.

4. Sustainable Manufacturing Indicator Repository Web Portal

Manufacturing companies are increasingly interested in assessing their sustainability performance. The SMIR is available [22] to provide a centralized access to sustainability indicators to help companies measure their sustainability performance. The sustainability indicator repository web portal provides the following:

1. Introduction to sustainability and indicators
2. Analysis of 13 publicly available indicator databases
3. Categorized indicator sets based on similarity and application of indicator
4. Search capability of related indicators (under construction)

Introduction to sustainability and indicators: This section includes basic information on sustainability, sustainability indicators, metrics and their importance. This section of the portal explains to the users the overall concept of sustainability, how it is measured and how to use the web portal. Figure 4 shows the indicator repository's opening page.

Analysis of 13 publicly available indicator databases: This section of the web portal describes each indicator in the selected indicator sets as mentioned in Section 2.

Figure 3. Indicator repository introduction

Categorized indicator sets based on similarity and application of indicator: This section consists of analysis and categorization of each indicator of these selected 13 indicator sets. Categorization has been made in five dimensions of sustainability: environmental stewardship, economic growth, social well-being, technological advancement, and performance management. An overall overview and a brief overview of each of these five indicator sets shows how users can use this analysis for further analyzing other indicator sets. Figure 5 shows the overview of the indicator repository. Figure 6 shows a snapshot of the indicator repository description.

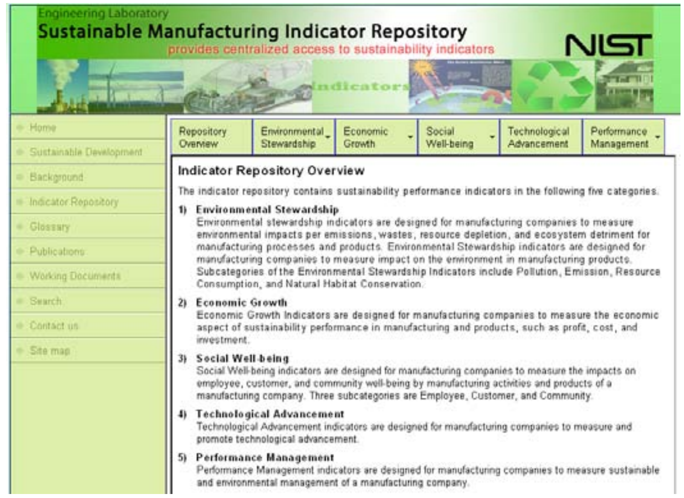

Figure 4. Indicator repository overview

Search capability of related indicators: This section is for enabling users to search for a particular indicator using different search criteria.

Figure 5. Indicator repository description

Apart from these functions that are available in the sustainable indicator repository web portal, a glossary of the definitions of terms, list of publications, and a site map is also provided. Provision has been provided to collaboratively work on analyzing indicators through a common sharing platform of sharing files through 'working documents' tab of the web portal.

There are several ways in which the small- and medium-sized manufacturing enterprises could use the information that is provided in the indicator repository web portal. Some of the possible ways are discussed below:

1. Understanding each indicator in detail: Users can access detail information regarding each indicator through this web portal. This portal provides users with description, usage, definitions, and categorization of each indicator. This portal also shows how to add a new indicator set to the existing set of 13 indicator sets, analyze it and categorize it. This portal provides a flexible approach to this categorization, so that stakeholders could possibly customize it.
2. Search for a particular indicator: There could be various instances, when a particular indicator needs to be searched for a particular application. Using this portal, different stakeholders could search for an applicable indicator for different purposes. For example, an indicator related to the environment applicable for a particular product, say a computer, could be searched. We are still developing this section.
3. Collaboration: Research and development on indicators would be an ongoing work for the coming decade. This portal provides provision to share files and collaboratively discuss indicators.

5 Conclusion

Sustainable manufacturing is a key idea in maintaining a high quality of life for current and future generations with the management of environmental, economic, and social issues. In the development of assessment methods for sustainable manufacturing, a wide variety of measurement indicators have been created. This great number of indicators has confused many manufacturers in specifically what to measure and how to interpret the results. The work presented in this paper attempts to organize these indicators in an expandable indicator repository with five developed dimensions of sustainability: environmental stewardship, economic growth, social well-being, performance management, and technological advancement.

The developed repository is the result of a comprehensive review of currently available indicator sets and indices, and their integration into sustainable evaluation on an organizational and/or process/product level. The placement of indicators from the various sets was made according to meaning and relevance of the given indicator based on a neutral definition. The result of the SMIR is a collection of indicators that provide an overall view of sustainability for manufacturing processes, manufactured products, and organizations.

The use of the SMIR is to educate manufacturers in using indicators for sustainability and will provide them with a competitive edge in meeting the demand of governmental bodies and customers in becoming more sustainable. The SMIR will also generate the necessary indicators and dimensions for measuring sustainability by the participation of such manufacturers with their review of the commonly used indicators. Along with these indicators, areas of improvement and further development will also be established through manufacturer participation. Relatively new indicators from dimensions, such as technological advancement and social well-being, are likely to be key dimensions for this development. Furthermore, the development of indicators in their measurement methods and calculation will also be a result from use of the indicator repository by the desire of companies to measure not only their sustainability on an organizational level, but a process/product level. With such advancements and with the use of the SMIR within the sustainable measurement infrastructure, sustainable manufacturing will become a measureable and attainable goal for industry. With this understanding and analysis of the indicator sets, the SMIR Web portal provides all indicators, analysis, and ways to collaborate. NIST hopes that the information provided in the Web portal along with the analysis would be useful to the small- and medium-size manufacturing companies.

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