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Categorization of indicators for sustainable manufacturing

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ABSTRACT

The manufacturing industry is seeking an open, inclusive, and neutral set of indicators to measure sustainability of manufactured products and manufacturing processes. In these efforts, they find a large number of stand-alone indicator sets. This has caused complications in terms of understanding interrelated terminology and selecting specific indicators for different aspects of sustainability. This paper reviews a set of publicly available indicator sets and provides a categorization of indicators that are quantifiable and clearly related to manufacturing. The indicator categorization work is also intended to establish an integrated sustainability indicator repository as a means to providing a common access for manufacturers, as well as academicians, to learn about current indicators and measures of sustainability. This paper presents a categorization of sustainability indicators, based on mutual similarity, in five dimensions of sustainability: environmental stewardship, economic growth, social well-being, technological advancement, and performance management. Finally, the paper explains how to use this indicator set to assess a company's manufacturing operations.

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1. Introduction

In the recent decade, there has been increased pressure on manufacturing companies to think beyond the economic benefits of their processes and products and consider the environmental and social affects. It has thus become the goal for manufacturers to promote manufacturing processes and manufactured products that minimize environmental impacts while maintaining social and economic benefits. This desire has been extended by many customers, who wish that their products be created in a sustainable manner (MIT Sloan Management Review, 2011). This situation has challenged manufacturing enterprises around the world to stay competitive in the market place by developing and implementing sustainable manufacturing techniques and tools. Manufacturers have started to find sustainability measurement solutions; however, few effective measurement methods are available for assessing the impacts of manufacturing on the environment and society.

At least eleven major indicator sets have been developed to analyze and score sustainability of manufacturing processes. Since the application field of sustainability assessment is wide and new, a number of measures and metrics by means of indicators, indices, and frameworks for analyzing sustainable manufacturing have also been developed. Existence of many indicator sets has created confusion among manufacturers when they attempt to select an operational set of indicators for assessing sustainability in manufacturing. Specifically, manufacturing enterprises have been challenged to decide which indicators to choose to evaluate their processes and products, and how they should interpret these indicators in making their processes and products sustainable. Sikdar (2003) states that no consensus exists on a reasonable taxonomy of sustainability-related metrics. Similarly, Gaurav et al. (2008) state in a literature review that major sustainability metrics are inconsistently defined and business-specific. For instance, the Organisation for Economic Cooperation and Development (OECD) (OECD CEI, 2003) Core Environmental Indicators (CEI) include 46 indicators to measure the impact of industrial activities on the environment in industrialized countries, while the United Nations (UN) Commission on Sustainable Development identifies 96 indicators (UN-CSD, 2007) to address environment deterioration due to human activities.

To address this challenge, the National Institute of Standards and Technology (NIST) has developed a categorization of sustainability indicators that classifies a large number of indicators into appropriate categories and subcategories. The categorization provides a reasonable structure to integrate inclusively all the possible indicators from which companies can choose to assess sustainability for their products and processes associated with manufacturing. The rest of the paper describes the research and development of the sustainability indicator categorization. Section 2 reviews a collection of publicly available indicator sets. Section 3 provides an analysis of

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indicator properties and criteria used to evaluate indicators. Section 4 presents the methodology to categorize these indicators into a hierarchal indicator map. Section 5 suggests how to apply the right indicators for company-specific sustainability measurement needs, and Section 6 summarizes this work.

2. Indicator sets review

An indicator set is a group of indicators that comprise a holistic view of sustainability. Combining indicators from the more common environmental, economic, and social dimensions and evaluating those indicators together is a practice to measure the sustainability on a much larger scale than individual indicators. Results from the measurement help companies 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 (Kibira et al., 2009; Ueda et al., 2009). In contrast to indicator sets, indices provide a more straightforward conclusion on the level of sustainability because they rely on weight-based mathematical methods to aggregate many indicators into a single score. An index aggregates several indicators, e.g., Environmental Vulnerability Index (consists of indicators of hazards, resistance, and damage). With a single score, a sustainability level can be set and used as a metric for performance. In regards to how to improve the sustainability, contrary opinions can be drawn because of the compositions and interpretations of the indicators of an index. Because of these difficulties, a number of indicators, sets, and indices have been developed by organizations in an attempt to match the various levels of decision making for sustainability. Various levels are from the process/product level, company/organization level, and nation/region level, to the global level (OECD, 2007).

Through a literature review, we found the following eleven indicator sets that are publicly available. They include many indicators that can be used to measure sustainability in manufacturing processes. A summary is provided as follows.

1. *Global Report Initiative* (*GRI*): the GRI is a voluntary sustainability reporting initiative for organizations. The GRI consists of 70 indicators that are identified within the three main dimensions of sustainability: economy, environment, and society. In reporting, an organization would record and report the actual numbers for chosen individual indicators. Using the report, the organization's sustainability performance according to the GRI or internal entities can be analyzed and tracked. The purpose of such reporting is for evaluation and tracking for decision-making at multiple levels of the organization including: management, operations, and internal or external stakeholders (GRI, 2006; Staniskis and Arbaciauskas, 2009).
2. *Dow Jones Sustainability Indexes* (*DJSI*): the DJSI assesses the financial and sustainability performance of the top 10% of the companies in the Dow Jones Global Total Stock Market Index. The results of the index are used as criteria for investors and investment firms. Analysis by media and stakeholders along with a questionnaire for the organization forms the basis of the index. The index evaluates the performance of a company in 12 criteria, covering mainly the economic dimension, but also includes some aspects of the environmental and social dimensions (SAM Indexes, 2007).
3. *2005 Environmental Sustainability Indicators* (*ESI*): the 2005 ESI was developed by the Yale Center for Environmental Law & Policy for measuring and evaluating environmental stewardship for regions and countries. The ESI is a single value index that is an aggregate of six policy categories and 21 core factors consisting of 68 indicators. An ESI value for one country is the average of 68 indicators within the 21 factors (ESI, 2005).
4. *Environment Performance Index* (*EPfI*): the EPfI, developed at Yale University, complements the ESI by assessing the policy performance of countries in reducing environmental stresses on human health, enhancing ecosystem vitality, and sustaining natural resource management. The focus of the EPfI is in its 19 indicators for which these environmental stresses are measured (EPfI, 2010).
5. *United Nations-Indicators of Sustainable Development* (*UN-CSD*): the UN-CSD developed by the United Nations (UN) Commission on Sustainable Development (CSD) assesses the degree of sustainable development of a country or region. The latest version of UN-CSD was finalized in 2006 and contains 96 indicators. The indicators are categorized by 14 themes that account for the economic, social, and environmental health of developing countries (UN-CSD, 2007).
6. *Organisation for Economic Cooperation and Development* (*OECD*) *Core Environmental Indicators* (*CEI*): the OECD CEI was designed for monitoring environmental conditions for sustainable development of member countries. The OECD CEI includes 46 indicators, which address a range of environmental, social, and economic issues (OECD CEI, 2003).
7. *Ford Product Sustainability Index* (*Ford PSI*): the Ford PSI considers sustainable indicators within the environmental, economic and societal dimensions that are specifically relevant to automobile manufacturing and services. Because of the specialization, Ford's PSI has eight indicators: mobility capability, life cycle cost, impact on life cycle global warming, life cycle air quality, sustainable materials, restricted substances, safety, and drive-by-exterior noise (Schmidt and Taylor, 2006).
8. *International Organization for Standardization (ISO) Environment Performance Evaluation (EPE) standard* (*ISO 14031*): the ISO 14031 is an international standard containing specifications for organizations to develop their own indicators for environmental performance measurement. In the informative annex of the standard, three categories are relevant to manufacturing: (1) operational performance, (2) management performance, and (3) environmental condition (ISO, 1999).
9. *Environmental Pressure Indicators for European Union* (*EPrI*): the EPrI is a comprehensive list of indicators of the most important human activities that have a negative impact on the environment. The EPrI contains 60 indicators that overview the pressure of human activities on the environment in 10 policy fields including air pollution, climate change, loss of bio-diversity, marine and coastal environments, ozone layer depletion, resource depletion, urban environmental problems, waste, water pollution, and water resources (EPrI, 1999).
10. *Japan National Institute of Science and Technology Policy* (*NISTEP*): the NISTEP report contains indicators that cover the technological advancement due to contributions and personnel skill level of a given organization through education, patents imported or exported, and scientific publications (Japan Science and Technology Agency, 1995).
11. *European Environmental Agency Core Set of Indicators* (*EEA-CSI*): the purpose of the EEA-CSI is to provide a set of manageable indicators for reporting. Measurements based on the EEA-CSI provide a means for prioritizing environmental improvements for countries in the EU (EEA-CSI, 2005).

3. Analysis of indicators

An indicator has been defined in several slightly different ways in literature (Heink and Kowarik, 2010; Veleva and Ellenbecker, 2001; Singh et al., 2009; McCool and Stankey, 2004). We found that the definition of indicator in the ISO 14031 informative annex was vague and informal. We, therefore, define an *indicator* as a measure or an aggregation of measures from which conclusions on the phenomenon of interest can be inferred. To categorize indicators in terms of their relevance and importance to sustainable manufacturing, a clear understanding of sustainable manufacturing is needed. According to the definition from the United States Department of Commerce, "sustainable manufacturing is the creation of a manufactured product with processes that have minimal negative impact on the environment, conserve energy and natural resources, are safe for employees and communities, and are economically sound" (DOC, 2008). The definition for sustainable manufacturing assumes three dimensions for sustainability (i.e., economic growth, environmental stewardship, and societal well-being). The analysis of indicators in this section includes an analysis of the coverage of the technical domain of each indicator set, criteria of evaluating an indicator, and characteristics of an indicator.

3.1. Domain coverage

The reviewed sets and indices provide simple aggregations through point-by-point consideration of indicators. The application of an indicator set or index ranges from an organizational-level assessment to a country- or regional-level assessment. Many sets and indices have a focus on the sustainable development of a region or country, such as ESI, EPfI, EPrI, EEA-CSI, OECD, DJSI, ISO 14031, and UN-CSD, mentioned above. One index is focused more on the process/product level for sustainable manufacturing (Ford PSI). One set is primarily focused on corporate technological capability (NISTEP). The recently published OECD Toolkit (OECD Toolkit, 2011) provides 18 indicators on manufacturing on input (material and its content), operation (energy, water, and emission), and products (environmental impact). The number is still limited. This limitation establishes the need of standard criteria and definitions for indicators. Standard indicators will provide a dependable and repeatable means for manufacturers when they evaluate their level of sustainability and allow comparisons between products, processes, companies, sectors, or countries. Based on the above mentioned sets, we selected, defined, and categorized indicators that can be used by engineers on the factory floor to evaluate sustainability of their manufacturing processes and manufactured products.

3.2. Evaluation criteria for an indicator

The following criteria have primarily been established by the Sustainable Measures Group (Sustainable Measures, 2009) with an extension from Moss and Grunkemeyer (2007):

- *Measurable*: a measureable indicator is one that can be simply and easily measured by quantitative or qualitative means within a given time frame for data collection and evaluation.
- *Relevant*: a relevant indicator is one that directly relates to a meaningful and purposeful aspect of sustainability per the manufacturing process under evaluation.
- *Understandable*: an understandable indicator is one that is easily interpreted by the community and lay people.
- *Reliable/usable*: a reliable/usable indicator contains trusted and accurate information from the organization or manufacturing process under evaluation.
- *Data accessible*: similar to reliable/usable, an indicator must be based on data and information that can be easily accessed and acquired within the organization or process/product system.
- *Timely manner*: data and information collection, calculation, and evaluation for an indicator must be done in a timely manner for informative decision-making.
- *Long term-oriented*: current indicators must ensure their future use, development, and adoption as an organizational or process/product sustainability standard.

3.3. Characteristics of an indicator

An indicator can further be characterized by the following attributes:

- *Identification* (*ID*): the unique alphanumeric identifier of an indicator.
- *Name*: the word(s) for the distinctive designation of an indicator.
- *Definition*: the statement expressing the essential characteristics and function of an indicator.
- *Measurement type*: the type of an indicator (quantitative or qualitative).
- *Unit of measure*: the unit of the value of the indicator.
- *References*: citable documents of existing indicator set(s) or specific indicator(s), based on which an indicator is adopted from existing set(s) or newly developed.
- *Application level*: the level in a hierarchical organization that the indicator is applied. Based on this information, policymakers or decision makers in the organization can set up their own sustainability metrics based on their business strategies.

4. Categorization of indicators in sustainable manufacturing

To address disintegrated indicator sets and the current ad hoc approach in developing them, this section describes details of indicator categories and an indicator repository where categorized indicators for sustainable manufacturing are accessible to public.

4.1. Indicator categorization approach

NIST's indicator categorization is based on five dimensions of sustainability: environmental stewardship, economic growth, social well-being, technological advancement, and performance management. Fig. 1 shows the top-level categorization and the first level subcategorization. The environmental stewardship covers environmental impacts from emissions, resource use, and ecosystem detriment from manufacturing processes and products. The economic growth dimension emphasizes costs, profits, and benefits accrued along with investments made by the manufacturing organization. Social well-being (Mihelcic et al., 2003; Labuschagne et al., 2005) considers the impacts on employees, customers, and the community from health and safety programs, satisfaction assessments, and career/educational development. Technological advancement accounts for the ability of a manufacturer to promote technological advancement through R&D staffing, expenditures, and high-tech products. Performance management concerns deployment of sustainability programs and policies and conformance to regulations. Placement of indicators from the various sets was made according to the meaning and relevance of the given indicator based on a neutral definition. With the selection, development, and placement of indicators in the structure of categorization, the result of the categorization shows an extensive collection of indicators that meet the overall concept of sustainable manufacturing.

As an example of how categorization is done, the indicators from the "Material" subcategory in the "Resource Consumption" category of the Environmental Stewardship dimension will be

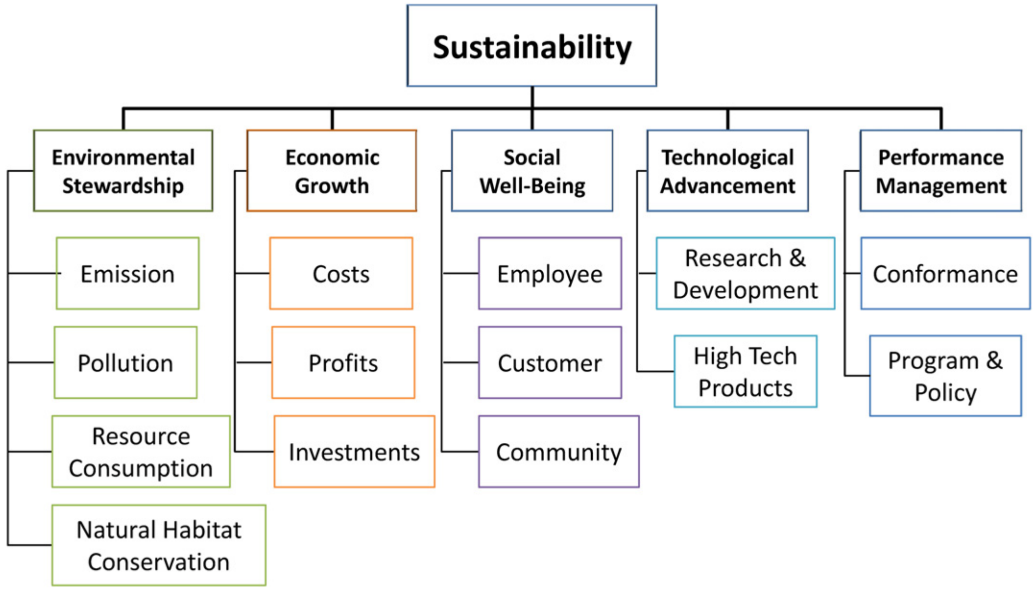
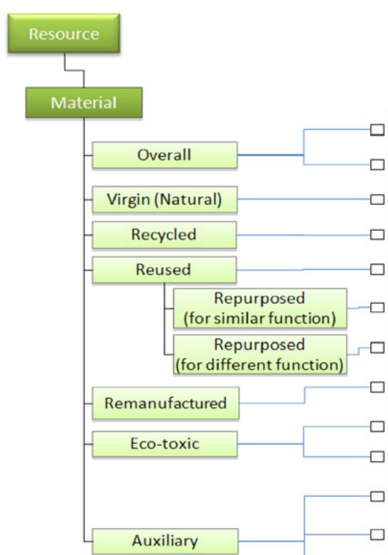


Fig. 1. NIST indicator categorization structure containing three main dimensions of sustainability, economic, environmental, and social, and two additional dimensions, technological advancement and performance management.



	Measurement unit	Measurement scope or scale (product / organization / time period)			Relevance to the available indicator sets				
	Val	/Prd	/Org	[t]	FORD-PSI	GRI-G3	ISO-14031	OECD-CEI	UN-CSD
Specific material used	#,$	o	o	o			v		
Material Intensity (total material used/total revenue)	%	o	o	Δ				v	v
Specific virgin material used	#,$	o	o	Δ	v		v		
Specific recycled material used	#,$	o	o	Δ	v		v		
Specific reused material used	#,$	o	Δ	Δ	v		v		
Specific repurposed (similar function) material used	#,$	o	Δ	Δ					
Specific repurposed (different function) material used	#,$	o	Δ	Δ					
Specific remanufactured material used	#,$	o	Δ	Δ	v		v		
Regulated eco-toxic materials used	#,$	o	Δ	Δ			v		
Regulated eco-toxic materials used by contracted service providers	#,$	o	Δ	Δ			v		
Materials used during after-sales servicing of products.	#,$	o	x	Δ			v		
Fluid consumption (oil, lubricant, coolant, solvent, etc.)	#,$	o	o	Δ					
Recyclable and reusable materials used by contracted service providers	#,$	o	Δ	Δ			v		
Percentage of products sold and their packaging materials that are reclaimed by category	%	o	x	Δ		v			

Legend : #: specific number, $: monetary value, %:percentage (rate), o: applicable, Δ: optional, x: not applicable, v: similar definition

Fig. 2. Example analysis of indicators derived from environmental stewardship dimension and resource category.

discussed. For the purpose of explanation, consider the first column 'material' under 'resources'. There could be several types of materials that are normally used for manufacturing. Some manufacturers use virgin material[1] to manufacture products, such as medical systems, whereas for other products such as plastic tables and chairs, recycled materials could be used. 'Material reused' could be further categorized into 'material that is repurposed for similar function' and 'material repurposed for different functions.' Upon defining the structure of the indicators, the relating categories and subcategories are listed in a spreadsheet. Next, a search of all the eleven indicator sets for these indicators is made and the indicators are then properly categorized in their subcategories (see Fig. 2). Also noted in this spreadsheet is the measurement unit and measurement scope for each indicator. This enables manufacturers to know how to apply the indicator. The last few columns of the spreadsheet show the frequency of these indicators in different indicator sets.

[1] Virgin material is the material that has never been used for manufacturing products.

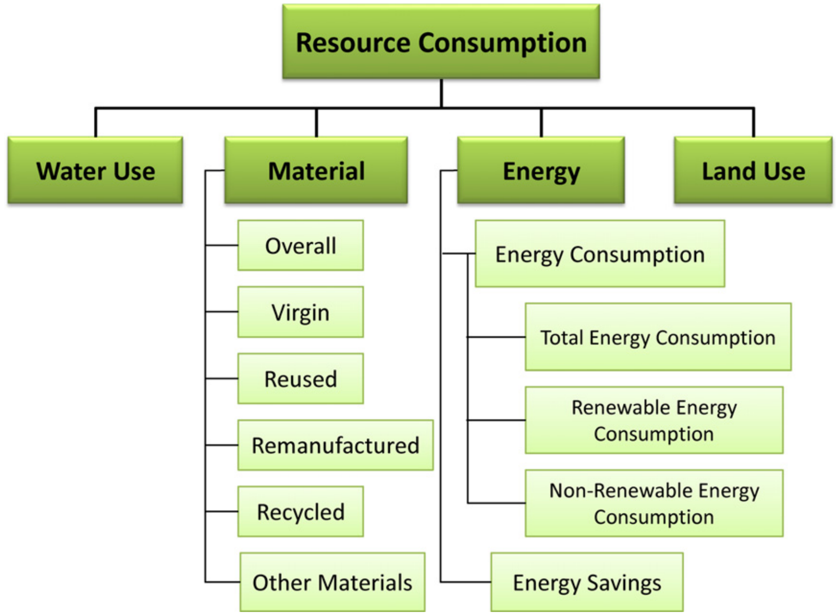


Fig. 3. Structure of resource consumption aspect within environmental stewardship dimension.

This gives a clear indication of how important this indicator is and its acceptance per its use in multiple sets of indicators.

4.2. Indicator repository

Further detail of this structure and the indicators within this structure can be found at the NIST's Sustainable Manufacturing Indicator Repository (SMIR) website (SMIR, 2011). The total number of indicators included within the SMIR is 212. Of the current indicators, 77 indicators belong to the environmental stewardship dimension, 23 to the economic growth dimension, 70 to the social well-being dimension, 30 to the performance management, and 12 to the technological advancement management. Each dimension is further categorized and described next.

4.3. Subcategorization

The number of indicators in each main category or subcategory indicates the size of that category or subcategory. The size of each subcategory is divided by the total number of indicators in the SMIR and the number of indicators in the main subcategory in which the subcategory belongs.

4.3.1. Environmental stewardship indicators

For environmental stewardship, a wide range of indicators were categorized per the impact of emissions, resource consumption, pollutions, and the natural habitat conservation.

- Emissions are categorized as follows: effluent, solid waste emission, air emission, and waste energy emission. Indicators in the emission subcategory are measured on the basis of what an organization or process releases during the production, along with the discharge of a product or service during its life cycle.
- Resource consumption is categorized as follows: water use, material use, energy use, and land use for an organization or process (see Fig. 3). The material consumption subcategory includes indicators of overall material consumption, virgin material consumption, recycled material consumption, reused materials, remanufactured materials, and other material consumptions. The energy consumption subcategory includes indicators of total energy consumption and energy saving.
- Pollution is categorized as follows: hazardous substances, Green House Gases (GHG), ozone-depleting gases, and other pollutants that are harmful to the environment (see Fig. 4).
- Natural habitat conservation is categorized as follows: biodiversity, habitat management, and conservation. This subcategory is needed to reflect effects on flora and fauna species along with the habitat in which they live.

Fig. 5 shows that Category 1: environmental stewardship contains the most indicators (77) accounting for approximately 36% of the SMIR. A large percentage of Environmental Stewardship indicators from the past research and measurement systems are focused on environmental sustainability. Of the reviewed sets and indices, the 2005 ESI, 2008 EPfI, EPrI, EEA CSI, OECD, and UN-CSD focus primarily on the environmental stewardship dimension. Along with these, many companies developed assessment tools, such as the Eco-Indicator and Life-Cycle Assessment that focus on the environmental dimension of sustainability. With such an established foundation, the future work for the environmental stewardship aspect should be on the further evaluation of the existing indicators, which have a number of uncertainties and difficulties in their data collection methods.

4.3.2. Economic growth indicators

The high-level structure for the economic growth dimension is presented in Fig. 1. Economic growth indicators measure profits, costs, and investments of an organization.

- Profit indicators are used for measuring the profit earned by the organization.
- Cost indicators are used for measuring costs from manufacturing, including material acquisition, production, product transfer to customer, and end-of-service-life product handling. These indicators are established from many manufacturers through basic financial accounting and life-cycle costing.
- Investment indicators are used for computing the impacts from general investments and eco-friendly investments, which collectively measure the economic health of an organization.

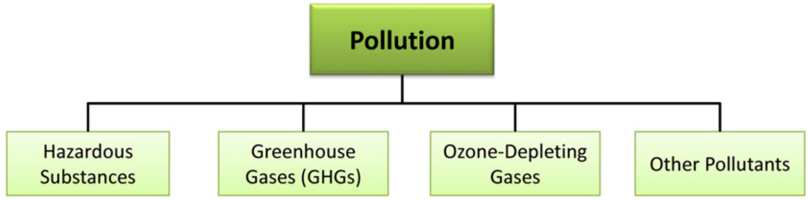


Fig. 4. Structure of pollution aspect within environmental stewardship dimension.

Investments and investment management are key aspects of the economic growth. Investments establish the growth of a product and/or company and sustainability of an organization. Within the investments aspect, general investments that promote financial and social growth of the organization are included along with green investments that encourage environmentally friendly investments.

Fig. 5 shows that Category 2: economic growth contains 23 indicators accounting for 10% of the indicators of the SMIR. Of the 23 indicators from the economic growth dimension, a majority of them come from the DJSI and GRI indicator sets. Many of the indicators within the economic growth dimension are part of long established cost accounting, benefit analysis, life-cycle costing, and risk management methodologies and have been widely used and accepted by a number of organizations. Therefore, the future development to the economic growth dimension should be not in the development of existing indicators, as with the environmental stewardship dimension. The further decomposition of operations and processes within the organization can provide more indicators within the economic growth dimension (Feng and Joung, 2010).

4.3.3. Social well-being indicators

Social well-being indicators measure societal impact of manufacturing processes and manufactured products through general health and safety practices, development management, and human rights by an organization. The social well-being dimension structure shows three basic aspects (see Fig. 6). Employees, customers, and the surrounding community are all directly and indirectly affected by the actions of an organization, and the consideration of these impacts is important to ensure socially sustainable operations and overall organizational sustainability.

- Employee indicators cover the overall health and safety of employees, their professional development, and satisfaction within an organization. The indicators within the employee aspect are necessary for sustainable manufacturing because of human rights issues, but also the close relationship between employee and product quality.
- Customer indicators cover the health and safety impacts from manufacturing and product-use, customer satisfaction from operations and products, and the inclusion of specific rights for customers. The customer subcategory contains indicators that reflect the ability of the organization to meet or exceed the demands and desires of customers. The customer satisfaction indicators are essential to measure customer satisfaction and well-being as those are dominant factors for the existence of an organization.
- Community indicators are directly related to an organization's actions. Subcategories are product responsibility, justice, and community development programs. Fairness, equity, human rights, and corruption are all included within the justice aspect of the social well-being dimension. Community measures are related to the organization's well-being through a healthy relationship with its community.

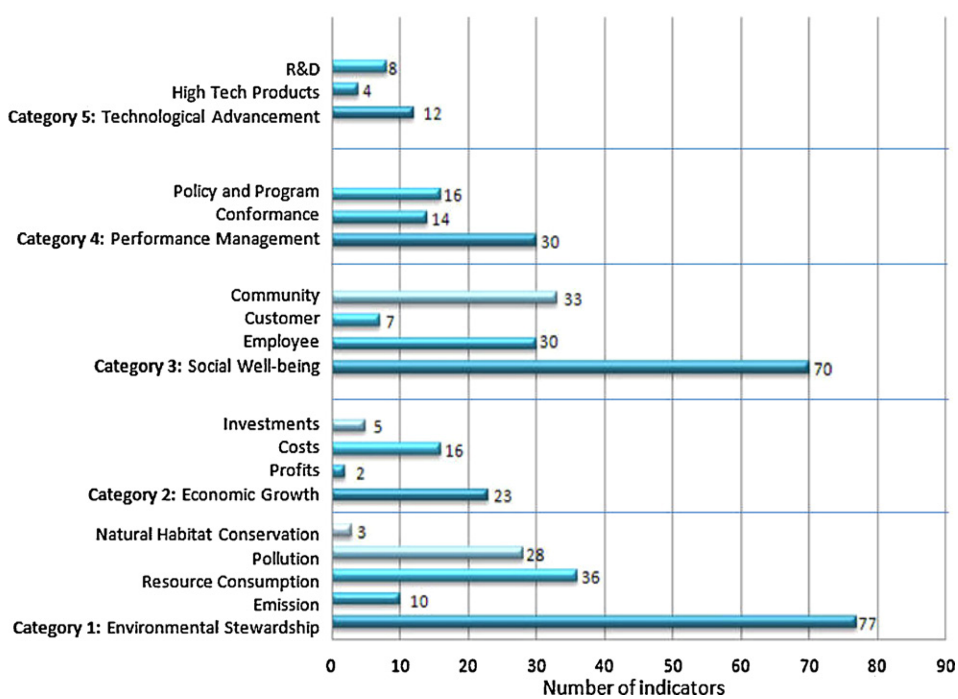


Fig. 5. Number of indictors in main categories and subcategories.

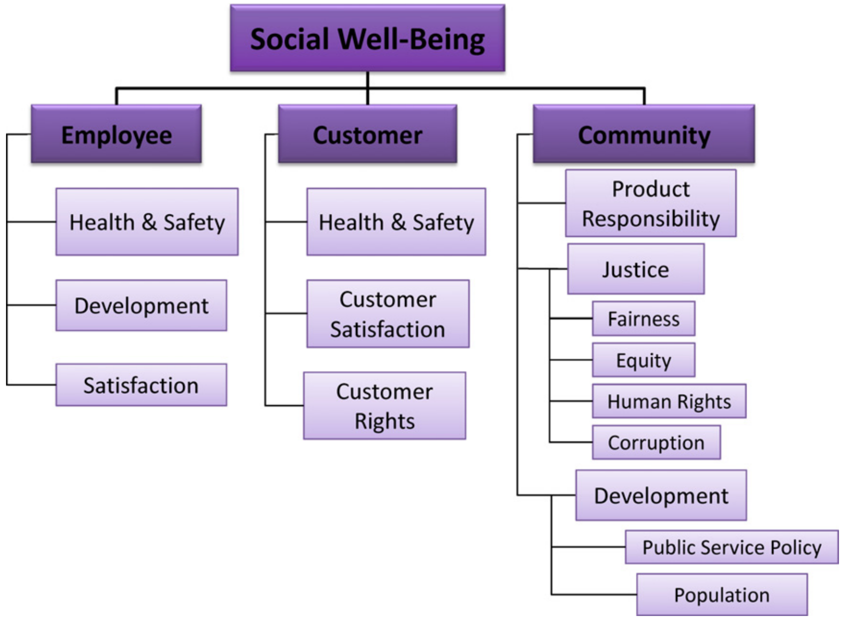


Fig. 6. Complete structure of social well-being dimension.

Fig. 5 shows that Category 3: social well-being is the second dimension as far as indicator quantity with 70 indicators accounting for 33% of the indicators of the SMIR. Most of the indicators within the social well-being dimensions are contained in the GRI indicator set. Since past research has pointed to a lack of measures within the social sustainability dimension, the large number of indicators is surprising (Visser and Sunter, 2002; Dreyer et al., 2006). This increase in number points to rapid development efforts within the social dimension. With this rapid development, the stability of social sustainability indicators is questionable. The actual impact of the social well-being indicators is yet to be established. Therefore, further development and study of these indicators is necessary for sustainability measure. In this development, an increase in quantitative measures is needed as many of the social well-being indicators are based on common scales or qualitative rankings. Furthermore, these indicators are heavily organization-based and not process/product-based.

4.3.4. *Performance management indicators*

The performance management indicators are not a dimension of traditional sustainability, but collectively and indirectly, measure the three main dimensions of sustainability. The complete structure of the performance management dimension includes specific management criteria for an organization with aspects in policy and program performance and conformance (see Fig. 1).

- Conformance indicators evaluate the ability of an organization to meet or exceed general and sector-specific guidelines for manufacturing processes and products. Conformance indicators are necessary to maintain high-level performance for the company, but also to sustain business through compliance to industry standards and safety regulations.
- The policy and program aspect contains performance indicators that consider the management of objectives and policies of an organization. The policy and program aspect within the performance management dimension can begin the basic 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.

Fig. 5 shows that Category 4: performance management contains 30 indicators accounting for 14% of the indicators of the SMIR. The performance management dimension is one of the additional dimensions to sustainability and primarily comes from the ISO 14031 indicator set, which has a focused subset on sustainable performance management. The majority of the performance management indicators also have organizational applications, so like the social well-being dimension, it will be necessary to further decompose the performance management indicators toward product/process level and determine their relevance and usefulness in regards to sustainable manufacturing. This indicates that the category is relatively underdeveloped. Moreover, development within this aspect may expand or contract the performance management dimension. A contraction may be required since some indicators have similar functions and/or measurement criteria, especially in regards to objective management and employee participation. Expansion of the dimension may also be needed for more product/process-specific criteria per conformance and public reporting, which in this repository has been reserved at an organizational application level.

4.3.5. *Technological advancement indicators*

Technological advancement indicators are designed for manufacturing companies to measure the new technology applied and R&D capability in manufacturing organizations. The focus is on the ability to promote technological advancement for the company.

- High-tech products indicators are designed for manufacturing companies to measure the quantity of new technology used, sold, and purchased by the companies for improving manufacturing processes.
- R&D includes the following:
  - 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.
  - Patents and published scientific papers establish the organization's level in innovative concepts and contributions per new technologies and products.

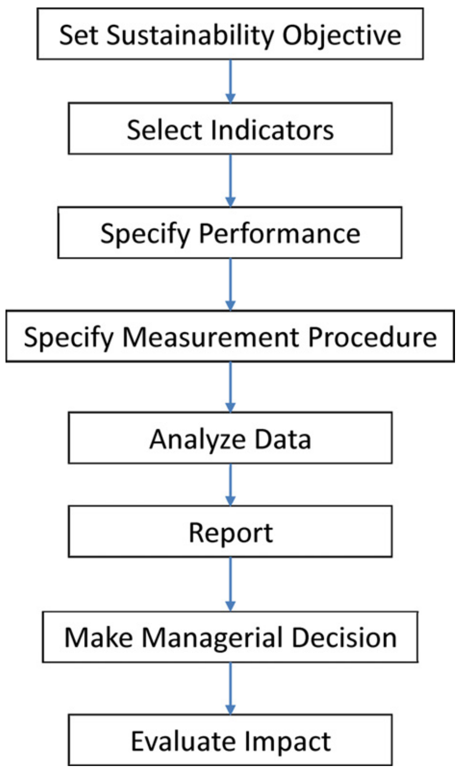


Fig. 7. Sustainability evaluation process.

◦ Scientific papers published by an organization are a benchmark in the contributions made to the scientific community to further technological developments.

Fig. 5 shows that Category 5: technological advancement contains 12 of the 212 indicators accounting for about 6%. The technological advancement category development relies heavily on the NISTEP indicator set, which was developed by the Japan Science and Technology Agency to assess the promotions of new and advanced technologies. Similarities with the Performance Management category show that the indicators within Technological Advancement are in need of further development and assurance. Of particular interest should be their effects and meanings in regards to the social, economic, and environmental dimensions. The concept of technological advancement for sustainable manufacturing is reasonable as new technologies will likely help an organization in regards to economic growth through advanced products and services, social acceptance through high demand, and environmental stewardship with new and innovative technologies that limit impacts. Expansion or contraction of this dimension may be necessary depending on such evaluations and studies.

5. Applicability of NIST indicator repository

With sustainability indicators, this section describes the applicability of these indicators to sustainability. It describes a proposed concept and methodology for measuring sustainability, based on a sustainability measurement infrastructure (Feng and Joung, 2009).

5.1. Determining applicable indicators

To evaluate sustainability, companies need to develop and implement a company-wide sustainability measurement process. Fig. 7 shows all the steps in the measurement process with a clear boundary between adjacent step(s).

Step 1: set sustainability objective
Sustainability measurement starts with a statement of the sustainability problem. The problem statement includes the sustainability challenges that need to be addressed, e.g., global climate change and toxicity release. In this step, a company needs to identify the problem from several perspectives: company, environment, and other stakeholders. Various methods for data collection and analysis could be used, such as interviewing managers, sustainability auditors, and study of past sustainability reports of the company.

Step 2: select indicators
The second step is to properly select applicable indicators to meet the sustainability objective, such as energy consumption, CO_2 emissions, and eco-toxic substance effluent. Selecting the right indicators depends on various factors, such as the type of product, type of processes, final reporting format, budget, approvals required, market, and time availability. Even when companies use experts to select the right set of indicators, this step is subjective as selection of the right set of indicators depends on many factors as stated above. Indicators can be selected from the indicator repository to measures causes, effects, and impacts on the environment, financial status, and social well-being.

Step 3: specify performance
This step is to determine the performance specification, which requires benchmark values. A benchmark value is a specified target value that the process or product has to meet, along with a specification of the acceptable uncertainty. An indicator is like a technical specification with a value and limits of the value. The manufacturer has to meet all the performance specifications in order to be successful.

Step 4: specify measurement procedure
This step specifies the measurement procedure for the selected indicators. The measurement procedure essentially consists of two steps: (i) finding the right measurement method and (ii) collecting the measurement result. A measurement method should include one or a sequence of measurement operations, measurement instrument selection, instrument setup specification, thorough documentation, and guidelines to measurement uncertainty reporting. Since indicators are quantitative, the measurement is more straightforward as the organization can rely on existing numerical models and simulations that provide an understanding of the system and indicator (Feng and Joung, 2009). In both data types, the measurement results include the statement of a measured value and the associated measurement uncertainty, such as described in the ISO standardized approach, Guide to the Expression of Uncertainty in Measurement (JCGM, 2008a,b).

Step 5: analyze data
The analysis of data is one of the most important steps of the assessment because it directly influences the final decision by the organization. Poor analysis could result in poor decisions that would make the manufacturing system or product less sustainable. A number of analysis techniques including qualitative, quantitative, and statistical techniques can and should be used. These techniques will also provide a way to generalize data. Generalized data will allow for ways to compare different data type indicators and their impacts, and could ultimately lead to an overall sustainability score. Further, such data analysis and values determination can allow for a comparison with the benchmarked values as determined in the performance specification in Step 3.

Step 6: report
Results from analyses have to be documented, and the performance metrics have to be officially reported. This step involves documentation and reporting of the entire work. A sustainability measurement report has the following elements: (1) the statement of the purpose, objectives, and scope, (2) administrative

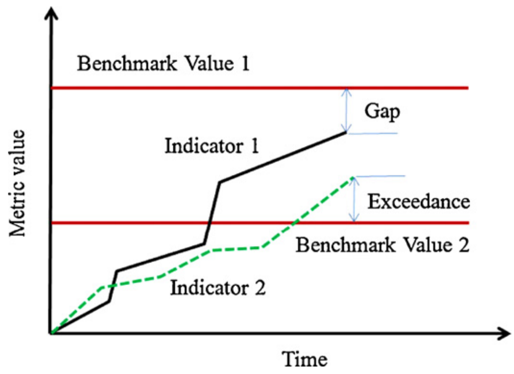


Fig. 8. Performance evaluation.

data, (3) contextual information, and (4) measurement results.

Step 7: make managerial decision

This step is to make managerial decisions within the company on how to improve the product design or manufacturing processes. In this step, managers need to prioritize their focus and develop a plan to improve their company's sustainability.

Step 8: evaluate impact

The final step is to evaluate the effects of improvements in the manufacturer's sustainability. The impact may be improved environmental performance, a company's financial improvement, and/or improved societal well-being, resulting from the solution to the identified sustainability problem.

5.2. Finding out different levels of achievement

A company measures manufacturing processes in the company's factory with respect to the selected indicators. The company can assign a benchmark value, as shown in Fig. 8, for each indicator used and then they compare their performance based on the difference of the measured value with the benchmarked value. The benchmark value of the indicator can be assigned either based on past performance of the company, by a particular standard, or by the amount of reduction required in a specific time period (e.g., a year). To meet the sustainability goal, all the indicators have to meet or exceed their respective benchmark values.

6. Conclusion

This paper presents available indicator sets and an indicator categorization for sustainability measurement. The purpose of categorization is to act as an organizational and educational tool for the manufacturing industry. The developed structure of categorization is an indicator repository containing more than 200 indicators within five sustainability dimensions. Further, this categorization is flexible and customizable. In the categorization of indicators, an extensive review of currently available indicator sets and indices was performed. Integration and categorization of these indicators into a structured map and repository were made by first evaluating the relative meaning of the indicators for a manufacturing enterprise per organizational and/or product sustainability measures. Placement of indicators was made according to meaning and relevance of the given indicator into an established indicator structure highlighted by five dimensions for sustainability from the various sets. This work results in a repository of indicators and their properties that collectively provide an infrastructure for measuring sustainability in manufacturing processes, manufactured products, and organizations. Finally, this paper also discussed ways in which manufacturers can use this work in assessing their sustainability performance.

Disclaimer

Certain commercial products may have been 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 that these products are necessarily the best for the purpose.

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