# An Overview of a Proposed Measurement Infrastructure for Sustainable Manufacturing


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**Abstract**

As the global resources depletion, climate change, and environmental pollution are worsening due to increasing globalized industrialization, manufacturing industry is under pressure to cope with the problems and maintain competiveness. Sustainable manufacturing has been proposed to meet the challenges faced by the industrialized countries. The measurement of sustainability in manufacturing is an enabler to quantitatively measure performance in sustainability in specific manufacturing processes. A sustainable manufacturing measurement infrastructure is proposed in this paper. The components include sustainable indicators and metrics repository, measurement methods, guidelines, and sustainability performance analysis and report. The sustainability measurement infrastructure provides a foundation for decision-making tools development and is expected to be tightly integrated into business strategy development processes.



**Keywords**:

Sustainable Manufacturing; Sustainability Performance Analysis; Sustainability Measurement.


## 1 INTRODUCTION

Manufacturing industries are confronted with a new major challenge on sustainability due to energy and natural resources being depleted, devastating global environment deterioration, and human beings pursuing higher life quality. In this circumstance, there is a critical need that manufacturing processes in products development must be sustainable. While it is a major component of civilized development to provide high quality human living standards, manufacturing itself is the main source of consuming natural resources with toxic by-products and wastes, often detrimental to the environment. In this context, the global research community has to develop new methods and metrics for sustainable manufacturing [1].

United Nations already defines that sustainable development is to meet present needs without compromising the ability of future generations to meet their needs [2]. In another view, sustainability in development is an organization's ability to advance its economic state without compromising the natural environment and the social equity that provide the quality of life for all community residents, present, or future. Therefore, sustainability is a competitive issue in all manufacturing sectors. According to the definition from 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 [3]. Design for manufactured products should have considerations on the entire product life cycle, including the manufacturer's economic benefits and the full impact of a produt on the environment and the society.

Organization for Economic Corporation and Development (OECD), one of leading organizations on promoting sustainable manufacturing, recently asserted several forward-looking activities [4]. One of them is to develop sustainable indicators, performance metrics, and analysis software toolsets to help business benchmark performance and improve their production processes and products. Additionally, American Small Manufacturers Coalition (ASMC) identifies a critical thread to U.S. manufacturing that sustainability measurement systems are inadequately deployed (ASMC news, June 11, 2009). A measurement infrastructure is critically needed to enable sustainable manufacturing.

This paper describes a development effort on a measurement infrastructure for sustainable manufacturing. Section 2 presents a study of current status on sustainable indicators and metrics development. Section 3 provides an overview of an infrastructure for measuring the sustainability performance in manufacturing processes. Section 4 describes an example to measure performance using an indicator. Section 5 summarizes the current development work and future directions.

## 2 BACKGROUND

Sustainability of an organization is often analyzed by three-dimensional perspectives: environment, society, and economy [5]. This multi-dimensional sustainability is often difficult to achieve because these aspects are interrelated in a complex way [6]. There are many within-company or international attempts to measure and analyze the performance of these three-dimensional sustainability by developing quantitative or qualitative sustainable indicators. These indicators are used to evaluate each dimensional performance, and can be shown in sustainability reports for stakeholders.

One of well-known international sustainability performance indicator sets is developed by the Global Reporting Initiative (GRI). Indicators in GRI are in two major categories: core and addition. They are categorized in these three dimensions: economy, environment and society. GRI is a voluntary initiative intended to provide a tool for decision-

Table 1. Various Sustainability Indicators & Metrics

| Indicator Set | components | Reference |
|---|---|---|
| Global Report Initiative (GRI) | 70 indicators | http://www.globalreporting.org/ReportingFramework/ReportingFrameworkDownloads/ |
| Dow Jones Sustainability Index (DJSI) | 12 criteria based single indicator | http://www.sustainability-index.com/07_htmle/publications/guidebooks.html |
| 2005 Environmental Sustainability Indicators | 76 building blocks | http://www.yale.edu/esi/ESI2005.pdf |
| 2006 Environment Performance Indicators | 19 Indicators | http://sedac.ciesin.columbia.edu/es/epi/downloads/2006EPI_Report_Full.pdf |
| United Nations Committee on Sustainable Development Indicators | 50 indicators | http://www.un.org/esa/sustdev/natlinfo/indicators/guidelines.pdf |
| OECD Core indicators | 46 indicators | http://www.oecdbookshop.org/oecd/display.asp?sf1=identifiers&st1=972000111E1 |
| Indicator database | 409 indicators | http://www.Sustainablemeasures.com |
| Ford Product Sustainability Index | 8 indicators | http://www.ford.com/doc/sr07-ford-psi.pdf |
| GM Metrics for Sustainable Manufacturing | 46 Metrics | http://actionlearning.mit.edu/s-lab/files/slab_files/Projects/2009/GM,%20report.pdf |
| ISO 14031 environmental performance evaluation | 155 example indicators | http://www.iso.org/iso/iso_catalogue/catalogue_ics/catalogue_ics_browse.htm?ICS1=13&ICS2=20&ICS3=10 |
| Wal-mart Sustainability Product Index | 15 questions | http://walmartstores.com/download/3863.pdf |
| Environmental Indicators for European Union | 60 indicators | http://biogov.cpdr.ucl.ac.be/communication/papers/tepi99rp_EN105.pdf |
| Eco-Indicators 1999 | 3 main factors based single indicator | http://www.pre.nl/eco-indicator99/ei99-reports.htm |

making in multi-levels such as, management, operation, and internal or external stakeholders [7]. GRI initiative gives a standard format of sustainability performance report so that manufacturers can benchmark the performance of their processes. Another worldwide framework for sustainability performance evaluation is the eco-efficiency assessment process developed by the World Business Council for Sustainable Development (WBCSD) in 2000 [8]. This framework provides activity-specific indicators and general indicators for all other activities. It recommends how to perform the entire eco-efficiency assessment process and the development of an eco-efficiency report. Different from the above two frameworks, which provide specific set of indicators, an international standard ISO 14031 provides recommendations to companies how to develop their own indicators for environmental performance [9].

Indicator developing frameworks, in general, can be summarized by several methodologies: (a) category or issue lists, (b) a goal-oriented indicator matrix, and (c) Pressure Source Response model [13]. In addition, sustainable indicator verifying checklist, such as community indicator checklist [10], may be useful in properly purposed indicator specification.

There are many general and sector-specific examples of developed sustainability indicators (see Table 1). Generally, the main issue of these indicator frameworks is that the focus is on the external reporting for stakeholders, rather than on internal information need to decision-making and re-design or optimization for actual eco-innovation. In this context, manufacturers need a standardized framework for the sustainable manufacturing environment, in which they could easily evaluate and track their sustainability performance.

## 3 SUSTAINABILITY PERFORMANCE EVALUATION AND MANAGEMENT

This section describes a proposed sustainability performance measurement infrastructure. Currently, key components in the proposed framework include sustainable indicator repository, sustainability measurement methodologies, and performance report (see Figure 1).

### 3.1 Sustainable Indicator Repository

Sustainability indicator repository contain all necessary sector-specific multi-dimensional indicators, representing the sustainability of the manufacturing systems, and metrics for performance benchmarking of the selected indicators within the eco-innovative business strategies. Sustainability indicators and metrics in the repository can be adapted from previous sets, shown in Table 1, or can be developed in a standard manner, ISO 14301. Adapted or developed Indicators, in general, should has some characteristics like below (partially from [10,11]):

- Measurable: Indicator must be capable of being measured quantitatively or qualitatively in multi-dimensional perspectives, e.g., economic, social, environmental, technical, etc.
- Relevant: Indicator must show useful meaning on the manufacturing processes under evaluation. It must fit the purpose of measuring performance.

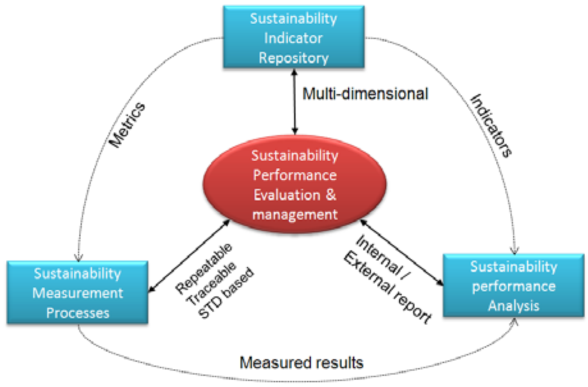


Figure 1. Key components of sustainability measurement infrastructure

- Understandable: Indicator should be easy to understand by the community, especially, for those who are not experts.
- Reliable/Usable: Information provided by indicator should be trusted and useful. Reliable measurement is necessary.
- Data accessible: Indicator has to be based on accessible data. The information needs to be available or can be gathered when it is necessary.
- Flexible: An indicator must be compatible with open standard expressions, such as ontology base and XML documents, to support long-term archival and flexibility for future generations.

In practice, sustainability metrics is a set of measurements, corresponding to standard indicators that are used to evaluate the sustainability performance of an organization. Based on measured results, enterprises can calculate their sustainability indicators, observe the trend of sustainability, and perform sustainability accounting. Figure 2 shows an example of time tracking of some metrics with respect to the targeted benchmark value. Time-dependent calculations of indicators let engineers or managers know the trend of specific metrics and the gap to the target at given time, and let them use the information in internal decision-making process for eco-innovation. Effective indicators allow engineers and designers to focus on specific areas of interest during the design process. Relying on "lumped"

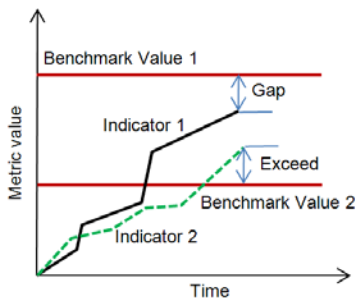


Figure 2. Tracking performance

metrics can be misleading if these metrics do not capture the competing drivers in the system. Ultimately, the quality and impact of engineering design are closely related to design of the metrics used in the analysis [12]; therefore, how to define and organize the metrics and indicators determines the effectiveness of them. In the sustainability indicator repository, an example Indicator hierarchy, which was developed by using category framework and the relationship with the product life cycle, is shown in Figure 3.

### 3.2 Sustainability Measurement Process

Sustainability measurement process is defined as a sequence of operations, with the necessary instruments and tools and having the objective of determining the value of an indicator. The main purpose has to be for internal decision-making and external accountability reporting; therefore, sustainability measurement process must contain the information of measurement process and instrument, target value(s), related object and indicator(s) according to the business strategies.

In 1999, Fiksel et al. [14] emphasized four sustainability measurement principles, which can help enterprise address the challenges associated with measuring and reporting sustainability: (a) resource and value, (b) triple bottom line, (c) product life cycle consideration, and (d) leading and lagging indicators. They pointed out that the sustainability performance measurement process usually involves three phases structure of plan, implement, and review. One of the main requisites of sustainability measurement is that every indicator is provided by standard-based measurement methods, procedures, instrument certifications and reference materials in a tightly integrated manner with business operations throughout the product life cycle. In this context, we set up several guidelines for measuring process below:

- Measurement operation sequence has to be logical and traceable so that it can be repeatable and comparable in time dependent product life cycle.
- Measurement instruments (data collectors) must be certified and calibrated in standard manner for the robustness.
- Sources and the magnitude of measurement errors is explicitly expressed.
- Expression of measurement uncertainty needs to confirm to open standards.

### 3.3 Sustainability Performance Analysis & Report

Based on the measured results, engineers not only report but also make necessary decisions for their business operations, such as redesign. The performance evaluation might be done in multiple passes with adequate analysis tools. Typical example of internal communication purposed evaluation is for the indicators to have a relation with their confidential business information, like manufacturing cost. In this case, existing practices, like enterprise resource planning or design for six-sigma [15], can be good tools for internal performance analysis and reporting. On the other hand, some indicators like enterprise-based green house gases or $CO_2$-emission are for typical external communication indicators. In this case, GRI can be a good tool for external communications. Business strategy and sustainability communication and reporting should, therefore, be linked with sustainability performance evaluation and management. To make this happen sustainability information

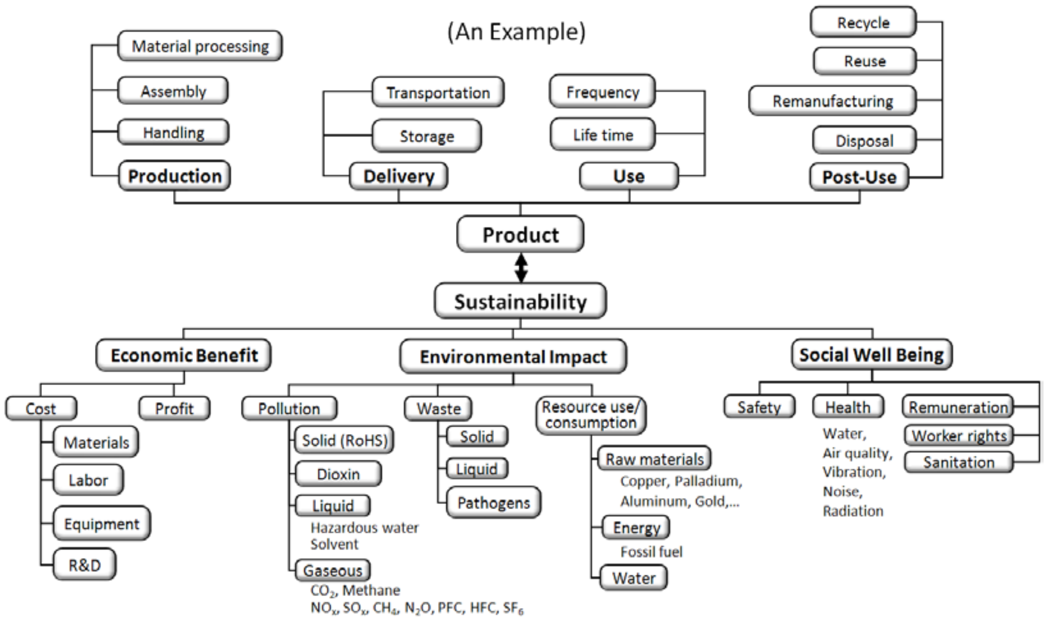


Figure 3. Indicators and product life cycle (an example)

and communication should be treated in the same manner as strategic planning and accounting [16].

Consequently, all the developed and selected indicators and metrics have necessary associations with standard measurement methodologies and instruments throughout the product life cycle. Engineers or designers can track the sustainability performance with indicators via standard based repeatable measurement methods. Furthermore, they can access measured metrics via various design analysis tools and use the results in their decision making processes for product eco-innovation.

## 4 CASE STUDY: $CO_2$-EMISSION

We introduce a simple machined subassembly example, adapted from [17] (see Figure 4). This subassembly consists of three components: A, B, and C. We assume that components A and B are machined directly by a company and component C is provided by a supplier. Machining operations that are applied to A and B within the organization of the company are shown in Figure 5.

### 4.1 Selected Indicators and metrics

Selected indicators and metrics in this example are shown in Figure 6. We used the calculation method of these indicators and metrics in [17]. First, used machining energy, $E$, in a

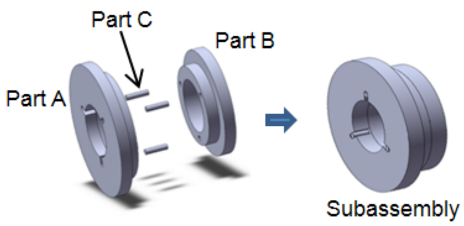


Figure 4. A machined subassembly (from [17])

single machining operations, is calculated by following equation[1].

$$E \pm \Delta E = k\int_{t_0}^{t_1} \left(F(t) \pm \Delta F(t)\right) * \left(v(t) \pm \Delta v(t)\right) dt \quad (1)$$

where, $F$ is cutting force [N], $v$ is cutting speed [m/sec] and $k$ ($2.77 \times 10^{-7}$) is a converting factor from W-s to kWh. Second, carbon weight (CW) can be converted by the energy used the following equation[2].

$$CW \pm \Delta CW = f \cdot (E \pm \Delta E) \quad (2)$$

where $f$ is a conversion factor for transformation energy to carbon weight (footprint) which can be found in Energy Information Administration (EIA) under U.S. Department of Energy (DOE). According to the report from EIA, the value of $f$ is 0.620 metric-tons/mWh in the state of Maryland [19].

### 4.2 Energy Measurement process

Energy used indicator is directly related by the energy metric. The indicator can be calculated by machining parameters like cutting force, surface speed, material removal rate, cutting time, etc. In general, these parameters can be monitored in real-time machine monitoring system, measured by dedicated instruments, and gatherd from machining system log, etc. For example, the monitoring system can report all machining parameters in XML format via network. A pricision machining center, in general, has a good control on velocity, so small varients on velocity can be neglected [17]. Besides, we approximate the process time ($t$) by computing the removal volume ($V_r$) for each process and assume that time dependent parameters, cutting force ($F$), surface speed($v$), and material removal rate ($R_r$), to be

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[1] We did not consider the energy for ancillary operations such as pumps, cooling media, etc. for a simple calculation.

[2] We did not take account carbon emission signature (CES$^{TM}$) concept as well. If CES$^{TM}$ were added, equation (2) would be replaced by $CW{=}E{\cdot}CES$ (See [18])

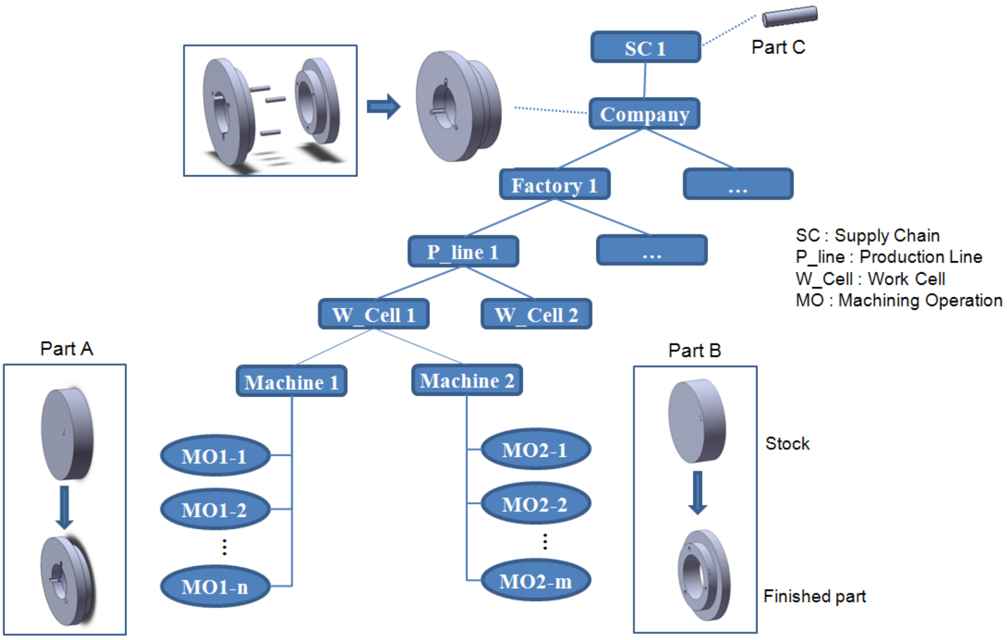


Figure 5. Manufacturing process of the selected subassembly example

constant. Hence the equation(1) can be approximated as equation (3).

$$E = k(F \cdot vt) = k \cdot F \cdot v \cdot \left( {V_r}/{R_r} \right) \qquad (3)$$

### 4.3 Metric Aggregation throughout an organization

All energy consummed in making a component or product can be calculated by accumulating the results in every single machining operations. To aggregate the assembly-level energy consumption from the components-level results, engineers evaluate indicators or metics at any level of the organization from operation to enterprise. In this case, calculated metrics table for Part A and Part B are shown in Table 2, where total carbon weight is a summation of carbon weights of all the parts. In this example, we do not consider the calculated value from supply chain.

## 5 SUMMARY AND FUTURE WORK

In this paper, we introduce an initial development of an infrastructure for sustainability performance measurement and management. This includes indicator repository, measurement process, and performance evaluation on the bottom line. In indicator repository, all developed or selected indicators, benchmark values, measurement methods, and computing algorithms will be available to public. Measurement process and the repeatability and reproducibility with the needed and alternative measurement instruments and tools should be traceable to corresponding measurement standards. A sustainability performance evaluation process is tightly integrated with business strategy for enterprise eco-innovation throughout the product life cycle. With the provided example, we showed how the metrics for the indicators can be measured within the manufacturing environment and showed the possibility of the aggregation throughout the all levels of the organization.

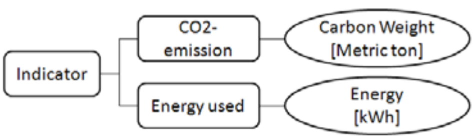


Figure 6. Selected indicators

The future work includes constructing a testbed environment for the proposed measurement infrastructure and the implementation guidelines for the integrated framework for a sustainability performance evaluation and management for eco-innovative sustainable manufacturing.

## DISCAIMER

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

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Table 2. Analysis of indicators at component process level

| Part | Parameters | | | | | | | Indicators | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | Oper-ations | Force $F$ [N] | Volume to be removed $V_r$[mm3] | Surface Speed $v$[m/s] | Process Rate $R_r$[$mm^3$/s] | Power [W] | Time t[s] | Energy Used [kWh] | | Carbon Weight [x$10^{-4}$ Metric Tons] | |
| | | | | | | | | E | ΔE | CW | ΔCW |
| A | OP1-1 | 742±5 | 291546.28 | 3.11 | 989.5 | 2308±16 | 294.64 | 0.1888674 | 0.0012727 | 0.117098 | 0.00078907 |
| | OP1-2 | 204±4 | 26116.47 | 4.26 | 426.67 | 869±17 | 61.21 | 0.0147762 | 0.0002897 | 0.009161 | 0.00017963 |
| | OP1-3 | 78±2 | 17002.84 | 3.45 | 63.33 | 267±7 | 268.48 | 0.020069 | 0.0005146 | 0.012443 | 0.00031905 |
| | OP1-4 | 40±2 | 22114.40 | 1.83 | 55 | 73.2±4 | 402.08 | 0.0081757 | 0.0004088 | 0.005069 | 0.00025345 |
| B | OP2-1 | 743±5 | 265660.96 | 3.07 | 989.5 | 2281±15 | 268.48 | 0.170114 | 0.0011448 | 0.105471 | 0.00070976 |
| | OP2-2 | 221±5 | 106804.03 | 4.1 | 426.67 | 906±21 | 250.32 | 0.0630047 | 0.0014254 | 0.039063 | 0.00088378 |
| | OP2-3 | 36±3 | 51346.46 | 3.16 | 216.67 | 114±9 | 236.98 | 0.0074886 | 0.0006241 | 0.004643 | 0.00038691 |
| | OP2-4 | 74±2 | 17002.84 | 3.33 | 63.33 | 246±7 | 268.48 | 0.0183776 | 0.0004967 | 0.011394 | 0.00030795 |
| | OP2-5 | 56±2 | 23722.72 | 1.83 | 59 | 102±4 | 402.08 | 0.011446 | 0.0004088 | 0.007097 | 0.00025345 |


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