Metrics, Standards and Industry Best Practices for Sustainable Manufacturing Systems

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***Abstract*— Substantial global climate changes due to global warming and the growing rate resource depletion have compelled several researchers to focus their research in the area of sustainability. Ensuring a sustainable future requires a systems approach. Sustainable systems are characterized by interlinked interactions at various levels spanning economic, ecological and societal issues. Emphasis on interactions within and across these levels is critical to the fundamental understanding of sustainable design and manufacturing systems, because tackling any one of the issues in isolation can result in unintended consequences along other dimensions. Sustainable systems are best understood in terms of information across products, processes, management (operational) aspects. In this paper, we outline several issues related to sharing this information across engineering and business units. We outline the information infrastructural needs to realize sustainable manufacturing, namely, trusted system of measurement methods and metrics, information models, simulation models, databases for toxic materials, and manufacturing products/processes, standards and best practices relevant to sustainable manufacturing, and validation, simulation and testing methodologies for information models and standards.**

Keywords: Sustainability, Metrics, Standards, information models

I. Introduction

THE 1987 report by the World Commission on Environment and Development (WCED), defined sustainable development as "Development that meets the needs of the present without compromising the ability of future generations to meet their own needs"[1]. A definition of sustainability according to the US National Research Council is "is the level of human consumption and activity, which can continue into the foreseeable future, so that the systems that provide goods and services to the humans, persists indefinitely" [2]. Other authors (e.g., Stavins et al. [3]) have argued that any definition of sustainability should include dynamic efficiency, should consist of total welfare (accounting for intergenerational equity) and should represent consumption of market and non-market goods and services.

Sustainable development aims for a future where products are 100% recyclable, where manufacturing itself has a zero net impact on the environment, and where complete disassembly of a product at its end of life is routine. What needs to be in place for this vision of the future to become a reality? Certainly there needs to be a trusted system of measures to support the nations' ability to monitor energy consumption, hazardous materials usage, and carbon output throughout the life cycle of manufactured goods, from raw material extraction through production and use of products, including ultimate disposal, recycling, remanufacturing or reclamation. There needs to be in place a measurement methodology to assign the energy and environmental costs at each stage of a product's life cycle. Information must be available at the early design stages about the eventual environmental costs of each design decision for a new product, and the decisions taken must themselves be recorded to support fair and equitable tracking. Information must be available at the end of a product's life to know how to properly dispose of or reclaim it. There is a need for new developments such as richer manufacturing and design standards that support energy and environmental information, better sensors and measurement technologies to monitor impacts on the environment, and methodologies for tracing life-cycle costs to a trusted infrastructure of measurements and standards that our economies can depend upon.

We believe that ensuring a sustainable future requires a systems approach. Sustainable systems are characterized by interlinked interactions at various levels spanning economic, ecological and societal issues. Emphasis on interactions within and across these levels is critical to the fundamental understanding of sustainable design and manufacturing systems, because tackling any one of the issues in isolation can result in unintended consequences along other dimensions. The primary goal of a systems approach is to capture and formalize descriptions of these processes and interactions. Because of the complexity of these systems, simulation and modeling will play a large part in understanding the overall impact of changes in any one part. To explain the suggested system approach of sustainability we need to realize the interaction among metrics, business objects, standards and desired information infrastructure.

Measurement of sustainability has been expressed by researchers in different ways [4, 5] but most definitions are based on the Triple Bottom Line (TBL) approach, e.g., with economic (profit), environmental (planet), and social welfare (people) objectives [6,7] (see Figure 1). Hecht [8] expressed that the three pillars of sustainability are economic,

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environmental, and social and that there is need for the system as a whole to be sustainable. To measure the impact of products on sustainability we believe that the impact should be measured in terms of the triple bottom line, considering all three indicators (e.g. planet, people and profit) together.

There are many researchers, who have proposed individual measures for environmental (planet) economic (profit), and social welfare (people) using various indicators (Figure 1) of which most of these are for assessing environmental impact of products.

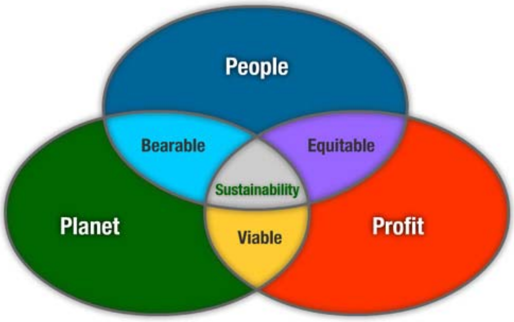

Figure 1. Triple bottom line (GI, 2009; Elkington, 1994)

II. System Approach to Sustainability

A sustainable product can be identified as a product which can be produced, distributed and used in a sustainable manner. A sustainable product can only be developed in a dynamic system working with ever-changing constraints, where inputs and useful outputs are optimized while harmful outputs are minimized. Figure 2 illustrates this concept.

A system consists of an enterprise at its core (Figure 2). The enterprise is driven by environmental, social and economical needs. The entire system works under various control parameters (**C**) such as availability of scarce resources, energy efficiency, and governmental and environmental regulations. The system gets resources from the planet as input (**I**) and generates useful and harmful outputs (output (useful), $\mathbf{O_u}$ and output (harmful),$\mathbf{O_h}$). There is also a feedback to this system from ***Ou*** in terms of 3R (reuse, recycle, and remanufacturing). The harmful outputs could be converted into waste to profit by the same company or could also act as input for other companies.

We believe that multidisciplinary research in feedback-controlled dynamical systems for sustainability can lead to a better understanding of the interactions among the multiple dimensions of economics, ecology and society.

Figure 2 also shows that there could be three kinds of enterprise. The first kind of enterprise consists of enterprises that do production, distribution and consumption. A typical manufacturing company falls in this category. The next kind of enterprise consists of companies such as distributers of white goods, which are engaged in distribution and consumption of products manufactured by other companies. The third kind of enterprise consists of companies such as government sectors which consumes products and are engaged in service to the society. All three kinds of enterprises are dependent on one another as they exchange services and exchange information across the entire life cycle of products.

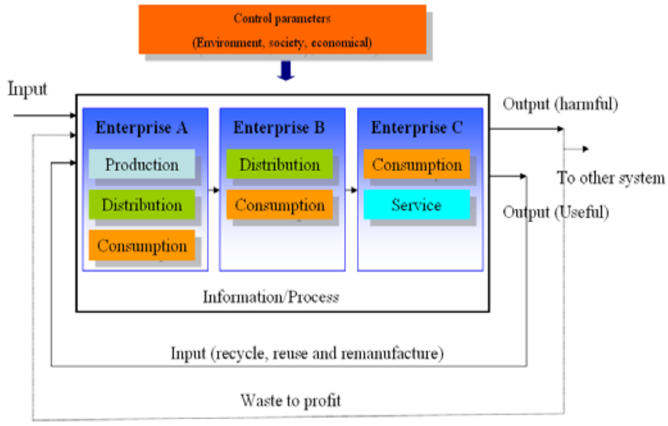

Figure 2. Proposed system for achieving sustainability within an enterprise

A. *Discussion on requirements for system thinking*

In this system thinking, we are trying to optimize Input, and outputs. We also need to minimize harmful outputs. All three kinds of inputs need to be optimized- input in the form of virgin materials, inputs in the form of feedback- 3R and inputs from converting waste to products. The common types of inputs are materials, water, energy and air. The control parameters of these enterprises are coming from external requirements- environmental, social and economical constraints.

For such system to interoperate we need to understand metrics, standards and business and information objects from a product manufacturing point of view. Sustainability standards have to work with product and process standards. We also need to see standards related to outputs and inputs that are related to these systems.

Once we have systems thinking we need to have metrics, standards and interoperability of engineering tools, business tools and life cycle assessment tools (Figure 3)- to take into account triple bottom line. Metrics are required to develop standards and standards affect information models and business objects. Presence of all of these together could help an enterprise to create a sustainable system.

Figure 3. Relation among metrics, standards and business objects

Interoperability and common accounting (to compute the triple bottom line) need to be systemized among business tools, enterprise tools and LCA tools in any enterprise and among other enterprises. Computing the TBL requires the following: information model, standards, tools, and information infrastructure. The following sections discusses on these issues. Section III talks about metrics, Section IV deals with standards for sustainability and Section V explains information models for sustainable manufacturing.

III. Sustainability metrics

The notion of sustainability has received some critical remarks. Scoping sustainability and defining clear system boundaries are critical for properly defining metrics for sustainable manufacturing [10]. Various metrics developed so far to measure the progress towards sustainability have been classified by Mayer [9] and Jain [11] into: a) indicators, b) indices and c) frameworks:

a). *Indicators* basically measure a single parameter of a system, e.g., CO_2 emission or energy use. Indicators can be classified into various types such as descriptive, normalized, comparative, structural, intensity, decomposition, causal, consequential, and physical. A detailed survey of indicators has been conducted by Patlitzianas *et al.*[12]. Keffer *et al.* propose a framework for developing a classification of indicators [13]. In the framework, indicators are classified based on aspects and categories. Categories are broad areas of influence related to environment, economy and society, referred to as the triple bottom line of sustainability. Aspects are defined as general type of data that is related to a specific category. Indicators then become the specific measurement of an individual aspect that can be used to demonstrate the status and performance of a system relative to a particular aspect and category.

b). *Indices* are basically aggregates of several indicators, e.g., Ecological Footprint (a ratio of the amount of land and water required to sustain a population to the available land and water for the population) or Environmental Vulnerability Index (consists of indicators of hazards, resistance and damage). Indices represent a single score by combining various indicators of different aspects of a system. Key requirements for sustainability indices, as proposed in Bohringer and Jochem [14], are:

c). Rigorous connection to the definitions of sustainability
    a). Selection of meaningful indicators representing the holistic fields
    b). Reliability and availability of data for quantification over longer time horizons
    c). Process oriented indicators selection
    d). Possibility of deriving political objectives
    e). Adequate normalization, aggregation and weighing of the underlying variables

    Scientifically sound methods of normalization, weighing and aggregation are a pre-requisite for construction of sustainability indices.

    The strengths and weakness of several sustainability indices are compared by Mayer[9]. The authors identify several issues across sustainability indices: system boundaries, data inclusion, standardization and weighing methods, aggregation methods, comparisons across indices. Rigorous mathematical requirements for indicators are presented by Ebert and Welsch [15].

d). *Frameworks* present large numbers of indicators in qualitative ways, e.g., the vulnerability framework [16] or the CRITINC Framework [17]. Frameworks do not aggregate data in any manner. An advantage of frameworks is that the values of all indicators can be easily observed and are not hidden behind an aggregated index. The disadvantage of using frameworks is that they are hard to compare over time although this is possible by using Hasse diagrams [18]. A brief review of sustainability frameworks is provided by Mayer [9].

Prabir et al [19] proposed a method to assess sustainability of engineering products using Triple Bottom Line. The primary approach taken by the authors is to define individual method to assess the impact of a product on planet (environment), people (society), and profit (economy) and then define a value based sustainability measurement method by considering all the three basic indicators of sustainability. Using analogy from nature in [19] a zero impact product is defined as one that can be (re)-manufactured again with only the material and energies which is left behind after its actual usage. Their work describes an approach that can be used during the product design phase to assess and reduce its environmental impact. Unfortunately, unlike natural systems, most artificial systems (or products) could not be manufactured with the same amount of material and energies left behind after the usage of these systems. The amount of deviation of a product from its ideal zero impact product condition is considered as the environmental impact of that product.

Our literature review shows a considerable proliferation of sustainability metrics that are inconsistently defined and business-specific. It is unclear whether one can define Core sustainability metrics, i.e., metrics that are uniformly defined and globally harmonized. Since core sustainability metrics are the ones that allow for a common definition of sustainability quality, we believe that there exists a vast opportunity for metrology to identify core metrics in the sustainability field.

IV. Standards for sustainability

Various standards have been developed in the last two decades to enable sustainable development. A summary of some of these standards is provided in Table 1. The list is not meant to be comprehensive and recommending a standards. These are just a sample of the available standards.

ISO 14000 standards create a systematic approach for reducing the impact on the environment due to the activities of an organization [20]. ISO 14000 standards include the ISO 14020 series for environmental labeling, ISO 14040 for Life Cycle Assessment, ISO 14064 for Green House Gases, to name a few. ISO 19011 provides guidelines for auditing quality and environmental management systems [21].

WEEE, is an acronym for the “Waste Electric and Electronic Equipment” directive [22]. WEEE directive makes the manufacturers of electronics equipment responsible for the waste. Therefore, the manufacturer should have the infrastructure available to recycle/reuse/process the waste equipment at the end of product's life.

RoHS stands for the "Restriction of Hazardous Substances" directive [23]. It lays down the limit (0.1% by weight) on the use of Lead, Mercury, Cadmium, Hexavalent Chromium, Polybrominated biphenyls and Polybrominated diphenyl ethers, separately, in electronic equipment.

REACH is an acronym for the "Registration, Evaluation, Authorization and Restriction of Chemicals" regulation [24]. It imposes health and safety *evaluation* of all chemicals of one ton or more by *registering* with European Chemicals Agency for *authorization*.

ELV stands for "End of Life of Vehicles" directive [25]. It is similar to WEEE, but is imposed on automotive manufacturers instead on electronics/electrical manufacturers. All electronic equipment in an automobile should follow the ELV directive. IMDS [26], IPC-1752 [27] and JIG-101[28] are acronyms for "International Material Database System," "Institute of Printed Circuits" and "Joint Industry Guide," respectively. IMDS manages materials for automotive manufacturers, while JIG-101 and IPC-1752 manage material for electronic equipments.

Table 1. Summary of standards for sustainability

Standard	Year	Region	Application
BS 8900 [29]	2006	British	managing sustainable development
ELV	2000	Europe	automotive vehicles
Energy Star [30]	1992	USA	products, buildings
EPA's AP-42 [31]	1995	USA	emissions factors for stationary sources
IEEE 1680 [32]	2006	USA	personal computer products
IMDS	2000	International	automotive industry material data system
IPC 1752	2007	USA	materials declaration in products
ISO 14000	1992	International	processes
ISO 19011	2002	International	environmental management systems
JIG-101	2005	International	materials declaration in products
LEED [33]	1998	USA	buildings, homes
NSF-140 [34]	2007	USA	carpet industry
REACH	2006	Europe	products with hazardous materials.
RoHS	2003	Europe	new electrical and electronic equipments
WEEE	2002	Europe	all waste electrical and electronic equip.

V. Information Model driven engineering for Sustainable Manufacturing

Understanding the effect of design and manufacturing decisions on sustainability requires the identification of the variables that contribute to the characterization of sustainability for the designed objects (products and manufacturing processes) in question. The clear definition of sustainability metrics is fundamental in gaining an understanding and identification of the parameters that define sustainable manufacturing. A consequence of developing these metrics could be characterization of a quality measure from different aspects of sustainability (material or energy flow models at different levels of granularity).

The degree of sustainability will be only as good as the quality of information used. Measurement of information and data quality is an open question that will have to be developed in the context of defining and validating information models for all aspects of product design including sustainability. In physical metrology there are established principles such as fundamental units, precision, accuracy, traceability and uncertainty. In order to understand and define quality for information and sustainability we need to develop metrological concepts similar to physical metrology appropriate for validation and testing.

The current lack of formal models (syntactically and semantically consistent representations) of product life cycle information makes it difficult to standardize and validate support systems for product life cycle management. We have identified the following classification of standards relevant to PLM support: (1) information modeling standards (languages), (2) content standards - domains of discourse and (3) architectural framework standards.

Failures in information exchange at the interfaces between design, engineering, manufacturing and other functions can be viewed as the Achilles heel of good product design. The ability of a firm to share relevant product descriptions and other information across the functional domains throughout the product lifecycle is critical to the firm's performance in the context of the forces of sustainability and globalization. A significant challenge of this program is to infuse information and methods for sustainability assessment in the design and manufacturing of products. To achieve sustainability goals across the product life cycle, the information infrastructure has to move beyond silos of information to a networked information infrastructure servicing all phases of the life cycle. A lifecycle support system that supports sustainability evaluations requires a move from product data exchange to product information and knowledge exchange across different disciplines and domains. Sustainability-based lifecycle support systems will need both syntactic and semantic interoperability through well-defined standards.

Model based engineering for sustainable manufacturing require information models, simulation models, databases for toxic materials, and manufacturing products/processes, and the following tasks needs to be carried out:

- Develop information models that provide key attributes that are necessary for sustainable manufacturing. This would include areas such as design for disassembly, carbon footprint, resource tolerancing, remanufacturing, recycling, energy resource management, hazardous material traceability and alternative processing technologies.

- Provide formal representations of information to support the full range of the product lifecycle beyond the representation of form (geometry and material),
- Develop information models to facilitate development of specifications of environmental performance measures to quantifiably evaluate the impact of a product or manufacturing process on the environment.
- Develop validated simulation reference models for manufacturing and construction processes that support consideration of alternative technologies and processes, tradeoff analysis, calculation of carbon footprints, evaluation of environmental impacts, etc.

In any manufacturing enterprise there are two types of tools used to create and share product related data across its extended network. The engineering information of the product is created using what is commonly called engineering authoring tool (e.g., CAD, CAE, PDM, and PLM). This information, encapsulated in engineering objects, mainly focuses on geometry and some amount of beyond geometry information. The business information, encapsulated in business objects, is created using business authoring tools (e.g., ERP, CRM, and SCM). Various solutions have been proposed to address interoperability issues within engineering tools and business tools. The prominent among them are standard-based, for example, STEP for engineering tools.

Global extended network enterprises have expanded their collaborative activities from marketing, planning, development, and manufacturing to include sustainability factors in products, processes and services. Sharing and exchanging product and sustainability related information among these partners is essential to guarantee an efficient collaboration along the network to realize maximum value from minimal resources. This information needs to be exchanged not only between different applications in the same domain, such as two different engineering applications (for example, CAx, PDM, PLM) or enterprise business applications (for example, ERP, SCM, CRM), but also between applications belonging to different domains, such as between engineering and enterprise business applications.

The main issue is to address the bigger problem of interoperability between engineering tools and business tools for sharing information relating to sustainability. Many information standards have been created to integrate applications and tools belonging to the same domain. Within the engineering domain, ISO-10303 (STEP) represents by far the most accepted standard, widely implemented in CAD, CAE and PDM systems. Many other standards within the engineering domain have been developed as spin-offs to STEP, for example OMG PLM Services. Within the business domain, the standards landscape offers a major variety of standards, mostly proposed by open and nimble organizations such as OMG, OASIS and OAGi.

While domain-specific standards have already been developed, the integration of standards belonging to different domains, although desired, still remains unrealized. In [1], Srinivasan noted that "time is ripe for such integration because of the convergence of three important factors: maturity of the domain-specific standards, emergence of SOA architecture for information sharing and availability of robust middleware to implement them".

VI. CONCLUSIONS

Innovative product development mandates the presence of 'sustainability' as one of the requirements during product design. Researchers have proposed various methods for assessing sustainability of products. Green manufacturing and sustainability initiatives are promising areas of research. Traditional product development generally aims for minimum capital maximum return that is products which adds values to the society and generates profit only. As resources are getting depleted and harmful effects of the wastes added to the environment are causing measurable ill effects on human life, companies and governments are getting actively involved in the development of products that are not only profitable and adds value to the society but also causes less damage to the environment. Sustainability is generally expressed in terms of Triple Bottom Line (TBL) - people, planet and profit. Products that are sustainable have positive effects on people, planet and profit and add value to each of them. Industry is recognizing that it must address manufacturing sustainability issues and that there are likely societal and regulatory pressures coming. What is lacking is the measurement and standards infrastructure needed to support the enforcement of such regulations. The future dominance of issues surrounding energy production, environmental impact, and most recently, greenhouse gases is hard to overstate.

Stricter environmental regulations controlling hazardous materials, scarce materials, and accountability for end-of-life handling of manufactured products are coming into play. We need scientifically grounded measurements and reliable technical standards to support these regulations. Carbon credit trading seems likely in the near future, resulting in a need to be able to quantify the carbon budget at each stage of manufacturing, and over the life of a product. It is clear that we need infrastructure of measurements and standards for such tracking. There is a critical set of requirements, from better sensors, less hazardous materials, new diagnostic techniques, environmentally benign manufacturing methods, and richer information sets to support informed decisions about production and disposal.

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