A Framework of Product and Process Metrics for Sustainable Manufacturing

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Abstract

This paper presents a framework for developing comprehensive product and process metrics for sustainable manufacturing, using machined products and machining processes examples, and addressing all three aspects of the triple bottom line – environment, economy and society. The need for developing standardized metrics is discussed for the wider use of these metrics by different manufacturers. The occurrence of similar measurements in some of the metric categories indicates the potential and need for data sharing between product and process metrics. The differences, relationships, and potential interactions between the product and process metrics are discussed from the viewpoint of their applications.

Keywords:

Sustainable manufacturing, Metrics, Products, Processes

1 INTRODUCTION

The U.S. Department of Commerce defines sustainable manufacturing as "*the creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound*" [1]. It is also stated that sustainable manufacturing includes both the manufacturing of "sustainable" products as well as the sustainable manufacturing of all products [2].

Sustainable manufacturing should consider the economical, environmental, and societal impacts, usually addressed as the triple bottom line. The impacts of the sustainability elements of a manufactured product and its manufacturing processes also need to take its entire life-cycle into consideration, which includes the four life-cycle stages: pre-manufacturing, manufacturing, use, and post-use. The analysis can be carried out on the product level, process level or system level. The innovation based 6R (*reduce, reuse, recycle, recover, redesign,* and *remanufacture*) approach allows for a significant transformation from a cradle-to-grave concept to multiple life-cycle consideration for a specific product [3]. The major product sustainability sub-elements identified, shown in Figure 1, consider all the 6R components.

Product and process metrics for sustainable manufacturing are necessary for evaluating the performance of a product or a manufacturing process considering the sustainability aspect. Aside from the basic application of proper evaluation of products and processes, the ultimate goal of developing product and process metrics for sustainable manufacturing is to provide improved decision-making criteria when optimizing product design and process design for sustainable manufacturing. Current metrics or indicators focus primarily on company, regional, national and global levels. Highly technical methodology of assessing sustainability performance of products and processes has not been fully addressed and there is a critical need for developing improved, comprehensive, and useful metrics for sustainability evaluation of products and processes [4].

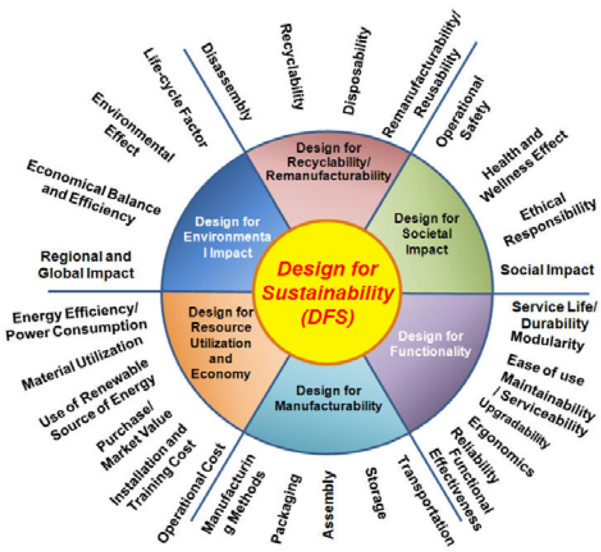

Figure 1: Product sustainability wheel [3]

This paper presents a framework for developing comprehensive product and process metrics for evaluating sustainable manufacturing of discrete products. Their relationships are also discussed from the total life-cycle viewpoint.

2 PREVIOUS WORK

Achieving sustainable manufacturing starts with the proper assessment of relative performance concerning sustainability in manufacturing. Ultimately, sustainability performance assessment requires commonly accepted standardized metrics. There have been many attempts that try to build such a system, and Feng and Joung [5] presented a comprehensive list of previous approaches.

Sustainable products are generally defined as those products providing environmental, societal and economical benefits while protecting public health, welfare, and environment over their full lifecycle, from the extraction of raw-materials to final disposal [6]. Previous work performed in the area of product sustainability has produced various indicators and metrics to evaluate the sustainability content. Fiksel et al. [7] developed a comprehensive list of product sustainability indicators and categorized these under environmental, societal and economic aspects.

Significant work has been done at the University of Kentucky in developing indicators and metrics for product sustainability. Jawahir and Wanigarathne [8], in their early work, identified six major sustainability elements and corresponding sub-elements in manufactured products, incorporating environmental, societal, and economic impacts. The broadly identified sustainability elements are as follows: environmental Impact, societal Impact, functionality, resource utilization and economy, manufacturability, and recyclability and remanufacturability.

Figure 2: Six elements of sustainable manufacturing processes [9]

Based on the triple bottom line considerations, a set of sustainability elements for sustainable manufacturing is proposed by Jawahir and Dillon [9], as shown in Figure 2.

Among these, the manufacturing cost, energy consumption and waste management are considered as deterministic elements, and the environmental impact, personnel health and operator safety are non-deterministic elements.

Seven guidelines for choosing an appropriate set of measurements in industrial applications were proposed by Fiksel et al. [10]. These are: comprehensiveness, controllability, cost-effectiveness, manageability, meaningfulness, robustness and timeliness. Feng et al. [4] also indicated seven characteristics of the sustainability performance indicators, requiring the metrics to be measurable, relevant and comprehensive, understandable and meaningful, manageable, reliable, cost-effective in data access and timely. In a recent General Motors report on metrics for sustainable manufacturing [11] the following five criteria that the metrics have to satisfy are proposed: (1) the metrics need to address the need of all stakeholders, (2) facilitate innovation and growth, (3) harmonize business units of different geographical locations, (4) be compatible with current value-adding business systems and (5) the related measurement needs.

Several researchers have investigated the environmental impact of manufacturing [12-16]. However, the ideas discussed mainly focus on environmental aspects only, even though elements of the economical and societal aspects are occasionally mentioned.

When performing manufacturing process optimization, defining the objective function is a critical issue. Conventionally, maximizing the productivity or minimizing the manufacturing cost is the usual target, subject to fulfilling quality requirements [17-19]. Preliminary work on machining process optimization with total sustainability as the target involves setting up a methodology to account for an incomplete set of indicators generated according to both the deterministic and non-deterministic elements of sustainable manufacturing processes [20]. However, a critical need remains for developing a comprehensive set of metrics for sustainability evaluation of products and manufacturing. The metrics should include a vocabulary and objective functions for sustainability optimization [20, 21].

This paper focuses on presenting a framework for developing comprehensive and practical product and process metrics for sustainable manufacturing, and presents the interrelationships and potential interactions among the metrics.

3 PRODUCT METRICS

In addition to considering environmental, societal and economic aspects and incorporating the 6R (Reuse, Reduce, Recycle, Remanufacturing, Redesign, and Recover) approach, a major emphasis is given to categorize the developed indicators and metrics into four stages in a product life-cycle. The four key stages of a manufactured product in a closed loop system are represented as follows: pre-manufacturing, manufacturing, use, and post-use [3]. Jawahir et al. [21] evaluated the sustainability content of a product using a generic product sustainability index (PSI), incorporating the three major components of sustainability (economy, environment, and society), over all four life-cycle stages. Numerous influencing factors are identified and categorized appropriately. The weights assigned to the influencing factors are arbitrary numbers based on their relative importance and company priorities. Gupta et al. [22] used the analytic hierarchy process (AHP) to determine the relative importance of different influencing factors and compare the sustainability content of two similar products

Table 1: Product metric clusters

	ENVIRONMENT	ECONOMY	SOCIETY
METRICS CLUSTERS	Residues	Cost	Education
	Energy Use and Efficiency	Innovation	Customer Satisfaction
	End-of-Life Management	Profitability	End-of-Life Management
	Material Use and Efficiency	Product Quality	Product Safety and Societal Well-being
	Water Use and Efficiency	Investment	Employee Safety and Health

Based on the six major sustainability elements and corresponding sub-elements of manufactured product metrics, as shown in Figure 1, a new product metrics system is being developed at the University of Kentucky. The metrics are grouped under a range of metrics clusters to make them more structured. The proposed metric clusters are defined for the environmental, economic and societal aspects, as shown in Table 1. Furthermore, several metrics have been identified and defined under different clusters to make the metrics system comprehensive. Some example metrics are shown (along with the clusters in which these metrics occur) in Table 2. All metrics are categorized across the life-cycle stages of a product to have a detailed understanding of the influence of a

Table 1: Examples of product metrics in different clusters, and the life-cycle stages to which they apply

Metrics Clusters	Example Metrics	Unit (D/L: dimensionless)	PM (pre-mfg.)	M (mfg.)	U (use)	PU (post-use)
Residues	Emissions Rate (carbon-dioxide, sulphur-oxides, nitrous-oxides, etc.)	mass/unit	√	√	√	√
Energy Use and Efficiency	Remanufactured Product Energy	kWh/unit		√	√	√
	Maintenance/ Repair Energy	kWh/unit			√	
Product End-of-Life Management	Design-for-Environment Expenditure	$/$ (D/L)	√			
	Ease of Sustainable Product Disposal for End Users	$/unit				√
Material Use and efficiency	Restricted Material Usage Rate	mass/unit	√	√		√
Water Use and Efficiency	Recycled Water Usage Rate	gallons/unit	√	√		√
Cost	Product Operational Cost	$/unit			√	
Innovation	Average Disassembly Cost	$/unit				√
Profitability	Revenue	$/unit			√	
Product Quality	Defective Products Loss	$/unit		√		
	Warranty Cost Ratio	$/unit			√	
Education	Employee Training	Hours/unit	√	√		√
Customer Satisfaction	Repeat Customer Ratio	(D/L)			√	
	Post-Sale Service Effectiveness	(D/L)			√	
Product Safety and Societal Well-being	Product Processing Injury Rate	incidents/unit	√	√		√
	Landfill Reduction	mass/unit	√	√	√	√

particular metric. An interesting observation while categorizing metrics across life-cycle stages is that some of these metrics have presence across multiple life-cycle stages. This provides an opportunity to organize metrics at different levels; for example, top level metrics can be the ones that are present across all four life-cycle stages. Further, the priorities derived through analytical techniques, such as the previously mentioned AHP, can be combined with this to obtain a system of levels which is more science-based. The ongoing work involves defining measurement methods to determine each metric quantitatively.

4 PROCESS METRICS

4.1 Process sustainability metrics

When evaluating a manufacturing process with respect to sustainability, each input and output needs to take into account the total life-cycle. A simple input/output chart of a manufacturing process, using machining as an example, is shown in Figure 3.

Metrics for a sustainable machining process are proposed by carefully examining the inputs and outputs of a machining process based on the six elements of sustainable manufacturing processes, shown in Figure 2. Examples of the metrics are shown in Table 3.

Use, reuse, recycle, and disposal aspects are considered whenever these life-cycle phases take place within the manufacturing process. For example, manufacturers buy new cutting tools and coolants and use these for a certain amount of work. After that, they may regrind the cutting tool and filter the coolant to make these applicable for further use. When the functionality is lost and/or goes beyond certain acceptable level, they will be disposed, either by sending to land-fill or by delivering to dedicated recycling plants. The cutting tools and coolants may have multiple life-cycles within the manufacturing plant in this sense, and the measurements represent the influence of the multiple life-cycles.

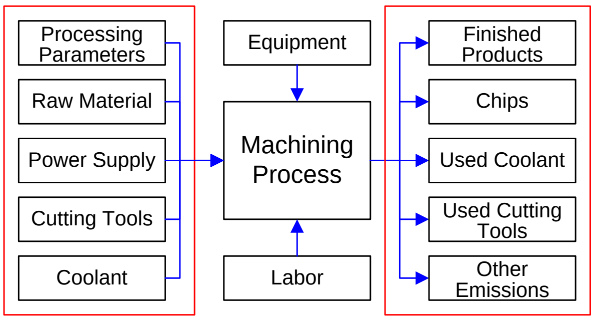

Figure 3: Input/output diagram for a machining process

For measurements of deterministic elements, the data can be collected onsite, experimentally measured, empirically predicted, or analytically calculated. For measurements of non-deterministic elements, by using fuzzy-logic techniques and creating a corresponding system of linguistic rules, the measurements can be quantitatively evaluated.

Table 3: Examples of process metrics for sustainable machining

Environmental Impact	Energy Consumption	Cost
GHG emission from energy consumption of the line (ton CO_2 eq./unit) Ratio of renewable energy used (%) Total water consumption (ton/unit) Mass of restricted disposals (kg/unit) Noise level outside the factory (dB)	In-line energy consumption (kWh/unit) Energy consumption on maintaining facility environment (kWh/unit) Energy consumption for transportation into/out of the line (kWh/unit) Ratio of use of renewable energy (%)	Labor cost ($/unit) Cost for use of energy ($/unit) Cost of consumables ($/unit) Maintenance cost ($/unit) Cost of by-product treatment ($/unit) Indirect labor cost ($/unit)
Operator Safety	**Personal Health**	**Waste Management**
Exposure to Corrosive/toxic chemicals (incidents/person) Exposure to high energy components (incidents/person) Injury rate (injuries/unit)	Chemical contamination of working environment (mg/m^3) Mist/dust level (mg/m^3) Noise level inside factory (dB) Physical load index (dimensionless) Health-related absenteeism rate (%)	Mass of disposed consumables (kg/unit) Consumables reuse ratio (%) Mass of mist generation (kg/unit) Mass of disposed chips and scraps (kg/unit) Ratio of recycled chips and scraps (%)

4.2 Hierarchy structure of the process metrics

A hierarchy structure of the process metrics is proposed. A sample is shown in Figure 4. In this hierarchy structure, the measurements are categorized into three levels: the manufacturing cell/line/plant level, the workstation level and the operation level. In a previous literature [4], the manufacturing system within a plant is considered as factory/line level, work cell level, machine tool level, and process level.

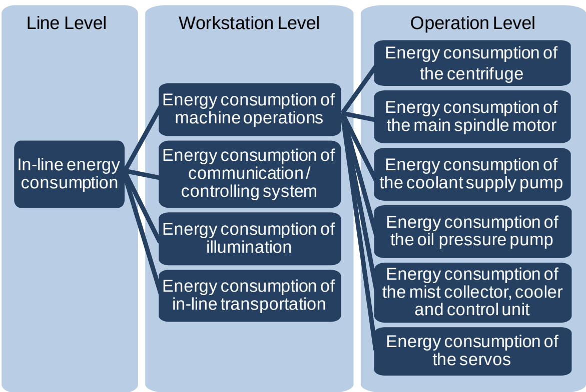

Figure 4: Hierarchical structure of an example process metric, listed in Table 3

With this hierarchy-based structure of metrics the widely accepted/standardized indices can be fit into the metrics properly. These indices can be either a high level measurement or a value summarized from the metrics. Furthermore, when current industrial applications fail to take the measurements in such detail at the operation level, or even workstation level, because of current routine or difficulty of application they might be able to collect data from higher levels. The data collected will be able to represent the influence of its sub-measurements on the indicators. The disadvantage is that the investigator may have difficulty utilizing presently available scientific models to build correlations between the input parameters and the higher level measurements, as the outputs of scientific models usually correspond to operation level measurements. The metrics proposed in Section 4.1 are actually a summary of line level measurements. It gives a guideline and overview of all the aspects which need to be evaluated.

At the operational level, all measurements focus on single process operations. The machine is doing a specific job with certain tools and materials under some particular set of operating conditions. In the case of machining, a single operation can be a face turning step or a hole drilling operation. The workstation level measurements focus on one single machine doing one or more operations or an accessory equipment providing some specific function. The plant/line/cell level includes the measurements inside the whole manufacturing unit. It can be a mass production flow-line, a manufacturing cell or a machine-shop plant, depending on the organization of the manufacturing facility.

All measurements at higher levels are composed of corresponding measurements at lower levels. In other words, with sufficient data from lower level measurements, we should be able to integrate them into the higher level measurements. Some measurements might appear under different sustainability elements, showing their influences on multiple aspects of sustainability. When calculating different indicators concerning these sustainability elements, different weighting ratios should be assigned to the repeated measurements as their importance and contribution towards that particular indicator would be different.

5 DISCUSSION

5.1 Relationships between the product metrics and process metrics from the life-cycle viewpoint

It is not surprising to see that some of the measurements in the product metrics and the process metrics are closely interconnected. For example, the manufacturing cost is considered in both the product and the process metrics. Furthermore, under the waste management element of the sustainable manufacturing process metrics, the proposed measurements take use, reuse, recovery and recycling into consideration, while similar measurements are considered in the sustainable product metrics.

The fundamental reason for the repeated measurements is that, a manufacturing process occurs in the “manufacturing” phase when considering the life-cycle of a product. On the other hand, if the manufacturing consumables or the production equipment is taken as the product under investigation, the "use" phase of their life-cycle occurs within the manufacturing processes. For the recycled and remanufactured products, the recycling and remanufacturing process is their "manufacturing" phase. The overall assessment therefore might be totally different. It suggests that the target under investigation has to be clarified at the beginning.

From the viewpoint of the products, manufacturing processes are a series of small periods in their life-cycles. Choosing the "correct" manufacturing processes, which is usually considered as process planning, involves selecting the optimized routine according to different criteria. These criteria can be conventional economics-oriented criteria, such as maximizing manufacturability, minimizing manufacturing cost and achieving best product functionality/quality, or relatively innovative sustainability-oriented criteria, such as minimizing environmental impact or maximizing societal benefits. The sustainability assessment of manufacturing processes provides a comprehensive criterion for total-sustainability-oriented process design.

5.2 Driving forces for data sharing

The nature of overlaps among the product and process metrics indicates the possibility and need for data sharing when carrying out sustainability assessment of a product or a manufacturing process. Judging from the measurements themselves, it is essential that the sustainability assessment data of manufacturing supplies, when considered as the product under investigation, should feed into the process metrics of the manufacturing process in which they are used. For example, the exact content of some specific coolant and the associated environmental impact will be used in the process metrics to judge the environmental impact of the used coolant. Similarly the sustainability data for a manufacturing process should feed into the product metrics of the product being manufactured by the process as the source for the "manufacturing" phase data.

Furthermore, as the data sources are often outside the domain under the investigators' control, the data collection of input materials as products can be difficult for the user. On the other hand, the product designer or the product sustainability evaluator carrier might have limited knowledge of the exact manufacturing process of the product. Also, taking the same measurements repeatedly by different investigators for similar purpose of using them would be a waste of time and effort. All of these point towards the need for data sharing between the product metrics and the process metrics.

However, there are problems when sharing the data for sustainability assessment. A very common problem is that different companies or industries use different business languages generated from their own company culture. Further, there are very few commonly accepted data formats. Even worse, interpretations of same words in different companies, industries, or countries can be very different. These problems are major barriers for data sharing among manufacturing organizations.

One of the important purposes of sustainability assessment of a product and its manufacturing processes is to identify areas with opportunity for improvement. It requires comparing different plants, companies or industries. A single set of measurements might be applicable when evaluating similar products manufactured with similar processes. However, it might be hard to compare the data measured for products coming out of different manufacturing processes or different geographical locations. The situation gets worse when comparing different products even when they may have similar functionality.

Both the data sharing and the comparison between different products require comparable data measured on correctly corresponded points. Thus, the sustainability metrics and data format for information exchange need to be standardized. The definition of measurements and correspondence of the data need to be addressed clearly.

5.3 Interface of analysis

The interface of analysis between the product and process metrics needs to be emphasized. As we can see in Figure 5, based on the product requirements, the product design phase would address a series of manufacturing output requirements. These requirements become the constraints of the process design. Though the ultimate goal is to implement the product performance expectations, the direct output of the process design is evaluated by the criteria provided by product design.

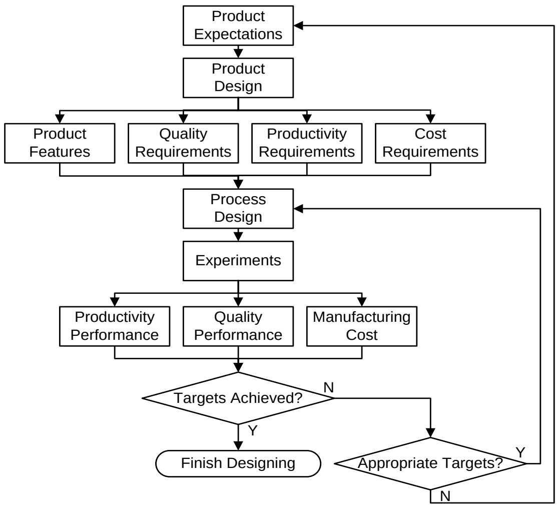

Figure 5: Relationship between the product design and process design

The sustainability assessments of a product, and its corresponding processes, have different emphases. The manufacturing processes, serve to implement a product design, and their constraints are decided by the current product design. To evaluate a manufacturing process, its fulfillment of product design features and requirements need to be considered. For sustainability assessment of a product design, the overall product sustainability performance is the ultimate criteria and the process assessment is only one of the sub-elements. To be specific, the sustainability assessment of a process would not cover the other phases of the manufactured product's life-cycle. The product assessment usually covers broader aspects than the process assessment, such as the entire life-cycle and 6R aspects.

An optimized manufacturing process routine does not necessarily mean that the product is optimal concerning its sustainability performance. On the other hand, to achieve optimal overall sustainability performance when designing a product, the corresponding manufacturing processes need to be optimized based on some sustainability criteria.

6 SUMMARY

This paper has presented a framework for developing comprehensive product and process metrics for sustainable manufacturing. The interactions among the two sets of metrics are discussed in view of the need for proper application of sustainability assessments. Potential need and possibilities for information exchange are also briefly introduced.

7 ACKNOWLEDGMENTS

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