A Total Life-Cycle Approach towards Developing Product Metrics for Sustainable Manufacturing

Ankur Gupta[1], Anshu Dhar Jayal[1], Michela Chimienti[2], I. S. Jawahir[1]

[1] Institute for Sustainable Manufacturing, and Department of Mechanical Engineering, University of Kentucky, Lexington, KY, USA

[2] Department of Mechanical and Management Engineering, Polytechnic of Bari, Bari, Italy

Abstract

This paper presents a total life-cycle approach towards developing comprehensive product metrics for sustainable manufacturing including the triple bottom line: environment, economy and society. The developed generic metrics are grouped under different metrics clusters, and are categorized across the four life-cycle stages (pre-manufacturing, manufacturing, use and post-use) of a product. This gives an opportunity to develop a leveling system for the metrics based on the presence of different metrics across multiple life-cycle stages. The development and deployment of relevant product metrics ontology is shown as a prerequisite for the ultimate evaluation and improvement in product design for sustainable manufacturing.

Keywords:

Product Life-Cycle; Sustainable Manufacturing; Product Metrics Ontology

1 INTRODUCTION

Sustainable products are generally defined as those products that provide environmental, societal and economic benefits while protecting public health, welfare and environment over their full commercial cycle, from the extraction of raw-materials to final disposition [1]. According to the National Council for Advanced Manufacturing (NACFAM) in the U.S., sustainable manufacturing includes the manufacturing of sustainable products, and the sustainable manufacturing of all products [2]. This signifies the importance of developing product-level metrics towards fulfilling the goal of sustainable manufacturing. Further, 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” [3]. This statement indicates the close interconnection between product-based and process-based metrics for sustainable manufacturing. The National Institute for Standards and Technology (NIST) has a well-established sustainable manufacturing group actively involved in the development of metrics for sustainable manufacturing [4].

Development of product-based sustainability metrics has been going on for a considerable period of time, and researchers in the past have suggested different ways to assess the sustainability content of a product. A large number of indicators for product sustainability are available in the literature. The triple bottom line aspect of sustainability (considering the environmental, societal as well as economic factors) is well known and accepted in the academia as well as industry. The quantitative evaluation of trade-offs among metrics across the triple bottom line is a difficult task, and this is one area where the ongoing research at the University of Kentucky is focused. It is a challenge to define and contain the system boundaries while trying to define the interrelationships among metrics across the triple bottom-line. A total life-cycle based approach helps to meet this challenge by developing metrics within the boundaries defined by the four life-cycle stages of a product.

2 TOTAL LIFE-CYCLE APPROACH TOWARDS PRODUCT METRICS DEVELOPMENT

A total life-cycle based approach towards developing indicators as well as metrics for product sustainability is the key element of the work presented in this paper. The categorization of metrics in this way provides an opportunity to develop a comprehensive list. The four life-cycle stages of a manufactured product in a closed-loop system considered here are: pre-manufacturing, manufacturing, use, and post-use [5]. Each life-cycle stage is defined in brief to understand its range of influence. This is critical because all the indicators/metrics are placed under different life-cycle stages based on these definitions.

Pre-manufacturing: The foremost stage in the life-cycle of any product is the extraction of raw material from the natural reserves. Pre-manufacturing includes mining metal ores and smelting them into metal alloys, extraction of crude oil and processing it into hydrocarbons, cutting trees and transforming them into usable wood or paper, etc.

Manufacturing: It is the phase where raw materials are transformed into finished products. A wide range of processing techniques is involved in this phase based on the desirable performance characteristics that are needed for the final product. Assembly (manual or automated), product packaging, etc., are also considered to be a part of the manufacturing phase.

Use: The use phase pertains primarily to the amount of time the consumer owns and operates the product. During its use stage, the product needs to be energy-efficient, safe, reliable, easy to operate, maintain and repair, etc.

Post-use: The post-use stage involves the final processing of a product for disposal, incineration, recycling, remanufacturing, or other end-of-life processing. Different end-of-life options can be considered during this stage to prolong the product life-cycle and also to ensure perpetual material flow in continuous development of next generation products from successive life-cycles.

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3 PREVIOUS WORK ON INDICATORS/METRICS FOR PRODUCT SUSTAINABILITY

Fiksel et al. [6] were among the earliest to develop product sustainability indicators and categorize these under environmental, societal and economic aspects. This work has a good aggregation of indicators, but with no total life-cycle consideration. Kaebernick et al. [7] and Ritzen and Beskow [8] developed procedures that consider environmental effects at the design stage of product development. Schmidt and Butt [9] developed a product sustainability index (PSI), which is implemented as a sustainability management tool in the Ford product development system. A significant part of the work in the product sustainability area is based on ISO 14000 standard series, which is pre-dominantly environmental, making it more of an environmental impact assessment. Further, no categorization across product life-cycle stages is performed. Consideration of four life-cycle stages across the triple bottom line has been an area of considerable emphasis from the early work done at the University of Kentucky [10].

4 PRODUCT SUSTAINABILITY EVALUATION USING INDICATORS

The six major elements of product sustainability along with numerous sub-elements identified in our early work are shown in Figure 1. These sub-elements form the basis for developing generic product sustainability indicators. Based on the requirements of different products and industrial sectors, these indicators can be selected. However, there is a need to combine these indicators and estimate aggregate scores/indices that can help to evaluate or compare different products in terms of their overall sustainability content. Jawahir et al. [11] evaluated the sustainability content of a product using a generic product sustainability index (PSI), incorporating the three aspects of sustainability and categorizing the indicators (influencing factors) across the four life-cycle stages of a product. The weights assigned to the influencing factors are approximate numbers based on their relative importance and company priorities.

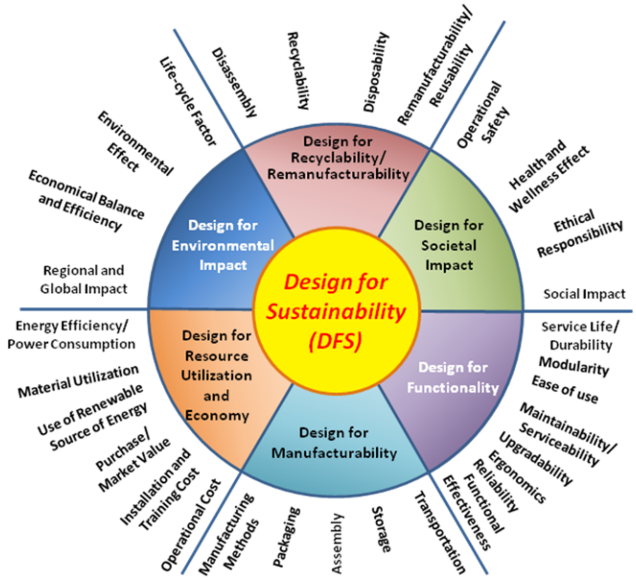

Figure 1: Product sustainability wheel [10].

Gupta et al. [12] used the analytic hierarchy process (AHP) to determine the relative importance of different influencing factors and compare the sustainability content of two similar products. AHP is a widely used mathematical technique that can prioritize a mixed group of elements with both qualitative and quantitative nature, minimizing the subjectivity involved [13]. Again, the life-cycle based categorization of the indicators is a key towards developing an AHP-based product sustainability hierarchy, as shown in Figure 2 for two different designs of a consumer electronic product (MP3 player). The life-cycle stages of a product form the Level L2 of the hierarchical structure in Figure 2. The corresponding influencing factors under different life-cycle stages are placed at Level L3 and this helps in designing a more comprehensive and accurate questionnaire, leading to a better evaluation of product sustainability content. After performing the AHP based matrix calculations, it was established that Product I is more sustainable compared to Product II. The overall priority values for all the influencing factors at Level L3 are also determined that helps in establishing the indicators that need prioritized attention.

Considerable interdependence is observed while developing the influencing factors or metrics for product sustainability. The interdependence refers to the influence of an indicator in one aspect over another indicator under a different aspect of sustainability (triple bottom line). Similarly, an indicator categorized under a certain product life-cycle stage can also have influence in other life-cycle stages. AHP methodology does not take this interdependence into account. The analytic network process (ANP), which is a generalization of AHP, can be used to study this interdependence and interaction of higher-level elements in a hierarchy on lower-level elements. The feedback structure used in this methodology helps in the decision making to attain a desired future [14]. The problem is structured as a network in ANP, rather than as a hierarchy. However, analytical calculations with ANP become very lengthy and complicated for a comprehensive set of influencing factors.

5 LIFE-CYCLE BASED LEVELING SYSTEM FOR PRODUCT METRICS

5.1 Life-cycle based leveling system

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 (Level 1) metrics can be the ones that are present across all four life-cycle stages. Level 2 metrics are the ones that are present across any three life-cycle stages. Similarly, Level 3 metrics are present across any two life-cycle stages and Level 4 metrics are only present in one life-cycle stage. Figure 3 shows a pyramid structure representation of these different levels of metrics. Further, Figure 4 shows the organization of metrics in the form of a Venn diagram. The four circles comprising the Venn diagram represent the four life-cycle stages of a product: pre-manufacturing, manufacturing, use, and post-use. Some example metrics (environmental, societal and economic) and the interdependence among these metrics are represented (through single and double headed arrows) in the Venn diagram. It can be easily noticed that the metrics presented as Level 1 need prioritized attention because of their influence across all life-cycle stages of a product. However, no weightings are assigned to any metric at this point which makes it difficult to ascertain if a Level 4 metric needs more attention than a Level 1 metric to enhance the overall sustainability content of a product. The metrics at four different levels set up the taxonomy of metrics, which can help in the future development of product metrics ontology. Ontology, which is an explicit specification of a conceptualization [15], and its challenging application in developing the metrics for product sustainability will be briefly presented in the last section.

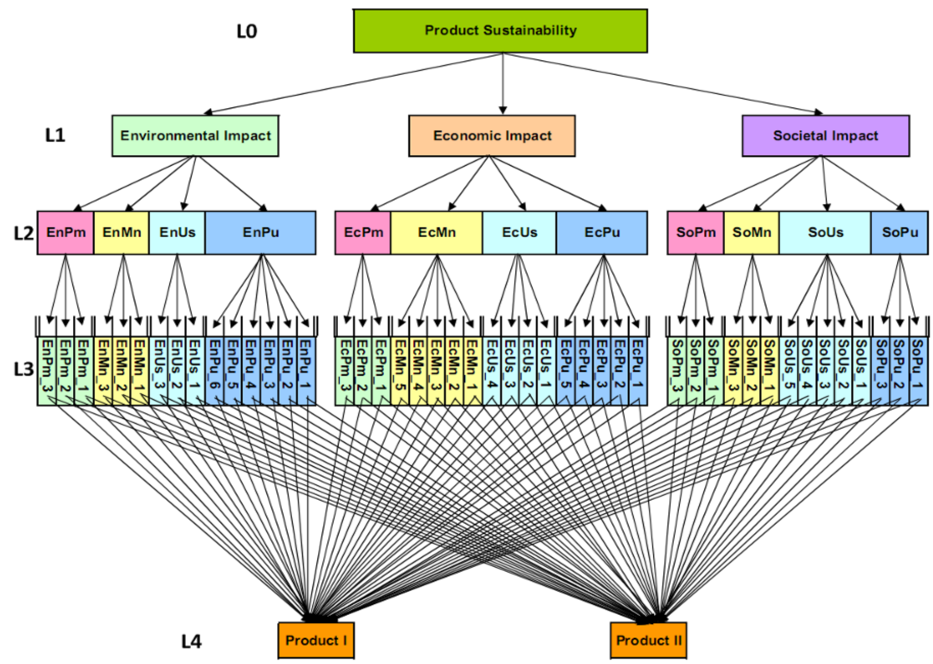

Figure 2: Product sustainability hierarchy [12].

Considerable subjectivity is involved in assigning the weightings to the metrics even in their current form as shown in Table 2. Further, any weighting system will be very product-specific. The application of AHP and ANP is a good approach that can be considered for assigning weightings to the metrics. A recent ANSI workshop also emphasized the need to have decision-making processes, such as AHP, that can be applied with flexibility based on varying needs for product sustainability standards [16]. The results obtained through AHP and ANP can be integrated with the data available for the metrics to derive more science-based weightings for a specific product. The recently undertaken case studies at the University of Kentucky involve automotive and aerospace products, and these case studies are expected to provide real-world examples for evaluating the actual product sustainability content.

5.2 Metrics clusters and product metrics

Based on the six major sustainability elements and corresponding sub-elements of product sustainability as mentioned before, a product metrics system is developed for generic products. The metrics are grouped under different metrics clusters to make them more structured. These metrics clusters have an important significance because these will help in a systematic aggregation of data while considering the complete life-cycle of a product. The proposed metrics clusters are defined for the environmental, economic as well as societal aspects, as shown in Table 1. There are 13 metrics clusters in total, with ‘end-of-life management’ being a common metric cluster across all elements of the triple bottom line. Several metrics are identified and defined under different clusters. 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 particular metric. Further, a generic measurement method is defined for each metric. This measurement method needs to be customized based on the product that is being evaluated. D/L stands for ‘dimensionless metric’ under the unit column in Table 2. The life-cycle based categorization of the metrics indicates the challenge involved in performing a complete sustainability evaluation for a product. The metrics that are present across multiple life-cycle stages will have a different measurement method under corresponding life-cycle stages. For example, if an automobile is under consideration, the ‘energy use’ during the manufacturing stage can be based on different processes and machines used. For the use stage, the same ‘energy use’ metric can be based on the miles per gallon etc. It should also be noticed that the product metrics under pre-manufacturing and manufacturing stages are mostly related to the processes involved with these products. The measurement method under these two life-cycle stages can be correlated to the methods defined for the process metrics. The process metrics development is not a part of this work. However, it is worth mentioning here because the close interactions between process metrics and product (pre-manufacturing and manufacturing stage) metrics can help in eliminating the redundancy involved.

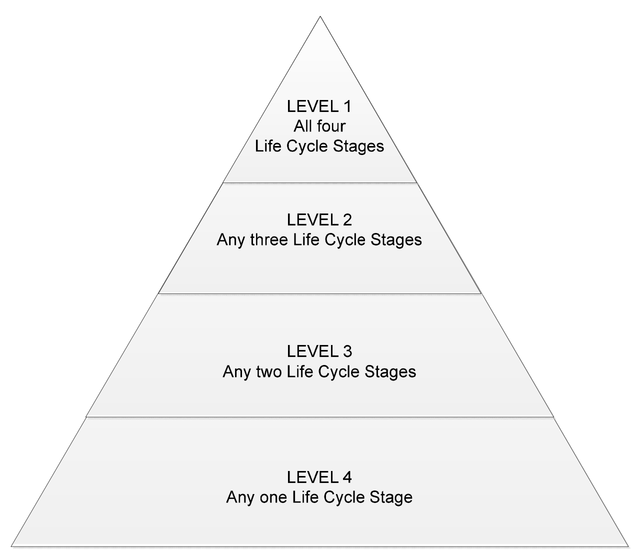

Figure 3: Leveling system for product metrics.

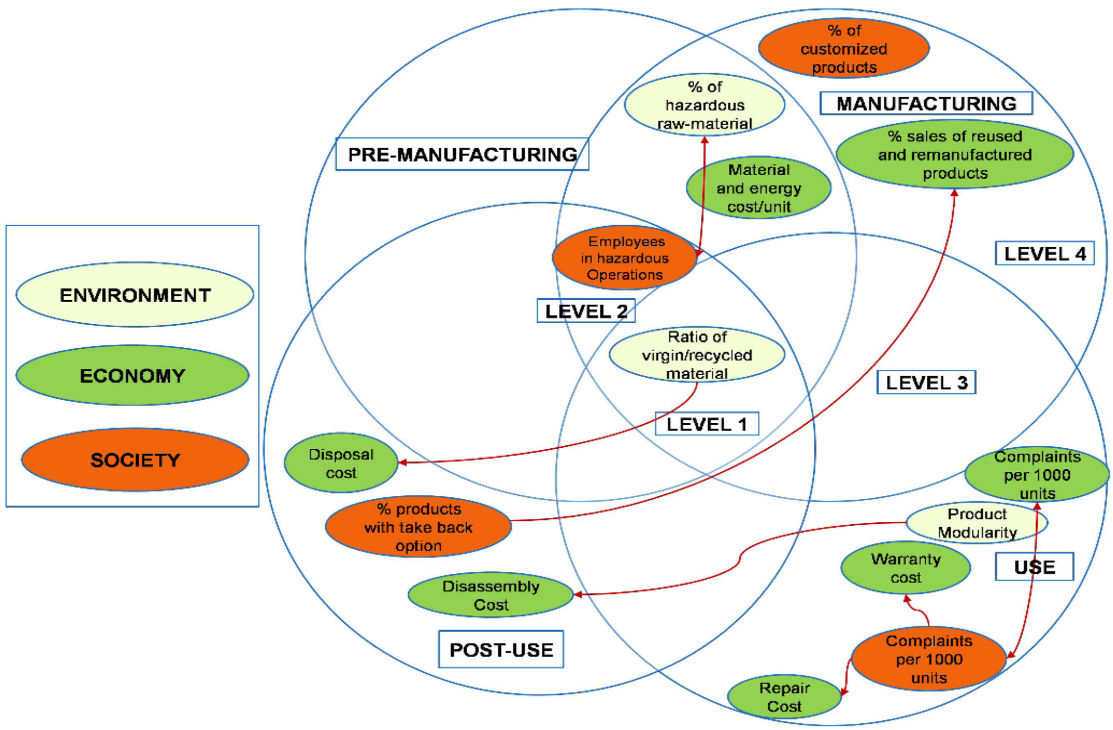

Figure 4: Examples of interdependence among indicators/metrics across life-cycle stages.

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

Table 1: Product metrics clusters.

6 TOWARDS AN ONTOLOGY-BASED APPROACH FOR PRODUCT SUSTAINABILITY

The analysis of developed metrics and their categorization shows that considerable interdependence exists among them across life-cycle stages and with respect to triple bottom line. It is important to account for these interrelationships when evaluating the sustainability of a product.

There is an increasing trend in developing software tools for product design and development. Most common among these are product life-cycle management (PLM) tools being developed by many companies. A significant amount of data for the pre-manufacturing and manufacturing life-cycle stages of a product overlaps with the manufacturing process-level data and a good integration between product master data and manufacturing master data would be needed. PLM tools provide a good environment to start and their use could be enhanced by including the various metrics clusters and developed metrics presented here. Furthermore, an ontology-based approach is proposed and considered as a solution towards improved product life-cycle management and thus improved overall product sustainability.

Fundamentally designed and used to improve communication between either humans or computers, ontologies are a good means to enable knowledge sharing and reuse. The main aim of ontology is to make explicit the knowledge contained within software applications, as well as that within an organization and the business procedures in a particular domain [17]. Considering that the metrics presented in the previous sections need to be defined and those definitions have to be adopted and understood by enterprise applications across the manufacturing system, the development of a product ontology which also takes these metrics into account is a sound solution for assuring and proceeding towards product sustainability. The ontology is often captured in some form of semantic network with nodes representing concepts or individual objects and arcs representing relationships or associations among the concepts [18]. The metrics clusters presented in Table 1 are good examples that can act as seed points for recognizing the ontology concepts. Also, the interdependence among metrics, as explained with the help of some examples in Figure 4, will help in representing the associations among the concepts of the ontology. This ontological approach will help in the development and deployment of relevant product metrics that will appropriately determine the overall product sustainability for sustainable manufacturing.

7 CONCLUDING REMARKS

This paper presents a generic product metrics system to assess the sustainability content of a product that can help in moving towards the goal of achieving more sustainable manufacturing. The metrics clusters and the corresponding metrics are developed so as to meet the needs across a broad range of industrial segments. An emphasis has been given to the life-cycle-based approach wherein the metrics are categorized across the four life-cycle stages of a product. Some analytical tools, such as AHP and ANP, are proposed along with data gathering that can help in assigning some weighting to different metrics.

METRICS CLUSTER	INDIVIDUAL METRICS	MEASUREMENT METHOD	UNIT	PM	M	U	PU
Residues	Emissions Rate (carbon-dioxide, sulphur-oxides, nitrous-oxides etc.)	Total Emissions (summing up different types of emissions and assign any weighting if possible)/ Total number of product units made	mass/unit				
	Solid Waste Stream	Mass disposed into landfill/ Total number of product units made	mass/unit				
	Liquid Waste Stream	Liquid residues (cleaning agents, coolants etc.) generated/ Total number of product units made	mass/unit				
Energy Use and Efficiency	Energy Efficiency	Net energy consumption/ Total number of product units made	KWh/unit $/unit				
	Maintenance/ Repair Energy	Average maintenance (repair) energy per product unit over the use phase/ Total number of product units made	KWh/unit $/unit				
End-of-Life Management (Environmental)	Design-for-Environment Expenditure	Research and Development expenditure to enhance environmental sustainability/ Total research and development budget	$/$ (D/L)				
	Reused Product Ratio	Number of reused product units sold/ Total number of product units sold	D/L				
	Remanufactured Product Ratio	Number of remanufactured product units sold/ Total number of product units	D/L				
Material Use and Efficiency	Restricted Material Usage Rate	Restricted material usage (Referenced from RoHS, REACH)/ Total number of product units made	mass/unit				
	Recycled Material Usage Rate	Amount of recycled material used (manufacturing phase)/ Total number of product units made	mass/unit				
	Packaging Material Usage Rate	Mass of recycled packaging material used/ Total number of product units made	mass/unit				
Water Use and Efficiency	Water Use Efficiency	Net water consumption/ Total number of product units made	gallons/unit $/unit				
	Recycled Water Usage Rate	Amount of reused or recycled water consumption/ Total number of product units made	gallons/unit $/unit				
Cost	Energy Cost	Cost of energy consumption/ Total number of product units made	$/unit				
	Product Operational Cost	Costs involved during the product operation over its life-span per product unit	$/unit				
	Product Maintenance Cost	Maintenance/repair costs involved during the product use over its life-span per product unit	$/unit				
	Legal Cost	Costs incurred on legal disputes (involving employees and customers)/ Total number of product units made	$/unit				
End-of-Life Management (Economic)	Average Disassembly Cost	Total disassembly cost/ Number of product units disassembled	$/unit parts/unit				
	Reused Product Profit	Average profit per reused product unit sold	$/unit				
	Remanufactured Product Profit	Average profit per remanufactured product unit sold	$/unit				
Innovation	Design Life	Average designed life-time of the product (compared with similar competing products)	Hours				
	Research and Development Cost	Research and Development costs on product sustainability related initiatives/ Total number of product units made	$/unit				
Quality	Life-cycle Span	(Actual average life span of the product unit)-(Designed average life span of the product unit)	Hours				

Education	Employee Training and Development	Average employee hours spent on training (related to product design, manufacturing, safety, quality etc.)/ Total number of product units made	Hours/unit $/unit				
Customer Satisfaction	Repeat Customer Ratio	Number of repeat orders for the product/ Total number of product units sold	(D/L)				
	Product Return Rate	Average products units returned/ Total number of product units sold	(D/L)				
End-of-Life Management (Societal)	Ease of Sustainable Product Disposal	Average cost involved in sustainable product disposal per unit of product disposed	$/unit				
	Ease of Product Take-back	Average cost involved per unit of product take-back after first-life of the product	$/unit				
Safety and Societal Well-being	Product Processing Injury Rate	Average number of injuries during product processing/ Total number of product units sold	incidents/unit $/unit				
	Product Use Injury Rate	Average number of injuries during product use/ Total number of product units sold	incidents/unit $/unit				

Table 2: Product metrics under different metrics clusters categorized across the life-cycle stages of a product.

Case studies on major automotive and aerospace products are underway to apply the metrics system. Further, an ontology-based approach is suggested as a pre-requisite for continuous improvement in evaluating the sustainability content of manufactured products.

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