Metrics-based Integrated Predictive Performance Models for Optimized Sustainable Product Design

B.M. Hapuwatte, F. Badurdeen, and I.S. Jawahir(✉)

Institute for Sustainable Manufacturing (ISM), College of Engineering, University of Kentucky, Lexington, KY 40506, USA
is.jawahir@uky.edu

Abstract. Implementing sustainable manufacturing principles and practices leads to innovation and sustainable value creation at product, process and system levels. In recent years, with the exponential growth in sustainable manufacturing research to meet the rapidly growing needs of industry and society, significant emphasis has been placed on designing innovative sustainable products and developing and implementing novel and advanced sustainable manufacturing processes to produce such sustainable products in automotive, aerospace, consumer products, biomedical and power industries. Sustainable manufacturing has been recognized as the driver for innovation in the manufacturing industrial sector. Achieving sustainable manufacturing targets inevitably requires a metrics-based analysis of sustainable manufacturing at product, process and systems levels.

This paper presents an overview of the 6R (Reduce, Reuse and Recycle, Recover, Redesign and Remanufacture) approach to promote sustainable manufacturing to enable closed-loop, multiple life-cycle material flow. The paper specifically focuses on sustainable product design for manufacture, with an in-depth analysis of product design and development processes by utilizing the novel 6R methodology. The transformation of conventional product design processes to sustainable product design/development is presented by expanding the recently-proposed metrics-based sustainable product evaluation method to include integrated predictive performance models for optimized sustainable product design. Designing sustainable products is presented as the most effective pathway towards promoting innovation and sustainable value creation.

Keywords: Sustainable manufacturing · 6R concept · Product development · Predictive performance models

1 Introduction

Sustainable Manufacturing: Definition, Goals and Impact. Sustainable manufacturing evolves from lean and green manufacturing concepts, and it offers a new way of designing innovative products and deploying manufacturing processes using methodologies that *minimize adverse environmental impacts, improve energy and resource efficiency, generate minimum quantity of wastes, and provide improved operational*

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safety and personnel health, while maintaining and/or improving the product and process quality with the overall life-cycle cost benefit [1].

The major goals of sustainable manufacturing are:

- Reducing *energy consumption*
- Reducing *waste*
- Reducing *material utilization*
- Enhancing *product durability*
- Increasing *operational safety*
- Reducing *toxic dispersion*
- Reducing *health hazards/Improving health* conditions
- Consistently improving *manufacturing quality*
- Improving *recycling, reuse and remanufacturing*
- Maximizing the use of *sustainable sources of renewable energy*

Sustainable manufacturing thus enables *cost-effective, environmentally-benign and societally beneficial innovative products and processes* serving as a basis for *sustainable value creation in manufacturing.*

Total Life-cycle Approach and Multi Life-cycle Products. Graedel [2] presented an extensive study of streamlined life-cycle analysis (SLCA) methods by considering five major product life-cycle stages: pre-manufacture; manufacture; product delivery; use; and recycling. Since the product delivery stage, including transportation, was considered as only one among several delivery activities involved across the life-cycle, the simplified total life-cycle of a product can be considered as consisting of only *four key stages: pre-manufacturing, manufacturing, use and post-use* [1]. To achieve multiple product life-cycles with the goal of near-perpetual product/material flow *facilitating the Circular Economy,* design and manufacturing practices for next-generation products must consider the *total life-cycle approach using innovative 6Rs* (Reduce, Reuse, Recycle, Recover, Redesign and Remanufacture). This in effect will enable sustainable value creation through innovation at all levels, in contrast to the perceived high costs of deploying sustainable manufacturing. Optimal secondary use of resources in sustainable manufacturing will lead to product/process innovation, and will provide cost-effective sustainable products.

Several other researchers have in the past attempted to quantify product sustainability. The sustainability target method (STM), developed by Dickinson and Caudill [3], correlates the economic value of a manufactured product with its environmental impacts. This method calculates resource productivity and eco-efficiency based on relevant indicators. It utilizes the estimation of earth's carrying capacity and economic information to provide a practical sustainability target and to determine if a product's end-of-life option is feasible [4]. A product sustainability index (*PSI*) method, developed by Schmidt and Butt [5] was adopted as a management tool for the sustainability assessment by Ford's product development group.

Figure 1 shows a methodology for producing sustainable products from optimized resources [1]. Developing model-based sustainable manufacturing methodologies by considering the total product life-cycle has been shown as a basis for product and process innovation in sustainable manufacturing [6].

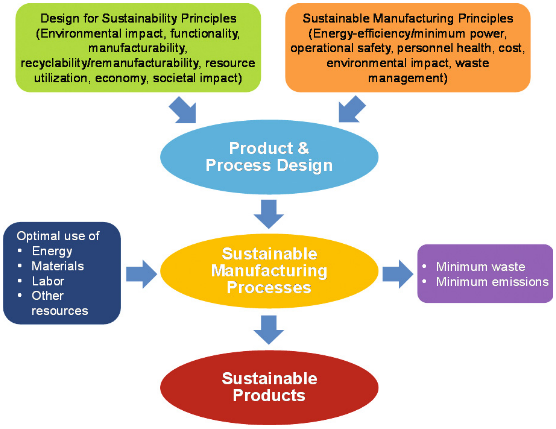

Fig. 1. Methodology for producing sustainable products from sustainable processes [1]

2 Metrics-based Product Sustainability Evaluation

It is essential to comprehensively evaluate a product's total life-cycle sustainability performance to successfully design and manufacture multi-generational sustainable products. To be effective, a metrics-based evaluation of sustainable products must integrate criteria that: (a) assess economic, environmental and societal performance, (b) consider impacts from pre-manufacturing, manufacturing, use and post-use stages of the product life-cycle, and (c) evaluate extent to which closed-loop material flow practices are implemented through the application of the 6R methodology. Beginning with early work by Fiksel et al. [7] which attempted to develop a quantitative method for product sustainability evaluation, prior studies have reported progress during the last two decades [8, 9]. Despite significant recent momentum in quantitative model development for product sustainability evaluation, most measurement schemes developed so far seem to lack in one or more of the above - (a) through (c) - required integral elements for comprehensive analysis of product sustainability.

Therefore, a more comprehensive approach to develop a framework and metrics that can help promote the design, manufacture and end-of-life (EOL) management of products to enhance the overall product sustainability becomes essential. This shortcoming has been addressed by a recent multi-year NIST-sponsored project [10] that involved an industry-university collaborative effort. The new framework developed under this project involves expansion of previously established six major product sustainability elements (environmental impact; societal impact; functionality; resource utilization and economy; manufacturability; and recyclability and remanufacturability) [11]. This effort resulted in a more comprehensive set of 13 clusters $[C_i \ (where\ i = 1, \ldots, 13)]$ developed for product sustainability evaluation. These clusters are categorized under the three triple bottom-line categories (TBL): economy, environment and society. A Product Sustainability Index (*ProdSI*) [12] is derived for manufactured products using a five-level hierarchical structure:

- **Individual metric (M_k):** a quantifiable and measurable attribute or property related to a single parameter or indicator of product sustainability (e.g.: recovery cost, material utilization, injury rate).
- **Sub-cluster (SC_j):** aggregation of metrics to evaluate performance of specific product sustainability aspects (e.g.: labor cost, EOL product reuse, safety).
- **Cluster (C_j):** aggregation of sub-clusters to assess product sustainability directly influencing the TBL categories (e.g.: direct/indirect costs and overheads, material use and efficiency, product safety and health impact).
- **Sub-index:** combining cluster values to determine performance along each of the three TBL aspects: economy, environment and society.
- ***ProdSI*:** the overall aggregated product sustainability performance index.

At each level of aggregation, normalization (to address unit of measurement variations) and weighting to integrate importance of one metric (w_k), sub-cluster (w_j), cluster (w_i) or sub-index (in this case, equally weighted) relative to the others are carried out. A complete list of metrics, sub-clusters and clusters with examples and corresponding life-cycle stage(s), can be found in [12]. The identified metrics for a given manufactured product can then be used to compute its *Product Sustainability Index (ProdSI)* using the expression shown in Eq. (1) with each C_i and SC_j computed as shown in Eqs. (2) and (3):

$$ProdSI = \frac{1}{3}\left(\sum\nolimits_{i=1}^{3} w_i^c c_i + \sum\nolimits_{i=4}^{8} w_i^c c_i + \sum\nolimits_{i=9}^{13} w_i^c c_i\right) \tag{1}$$

$$C_i = \sum SC_j w_j^{sc} \quad \forall i \tag{2}$$

$$SC_j = \sum M_k w_k^m \quad \forall j \tag{3}$$

Results from applying the metrics-based method to a manufactured product is shown in Fig. 2. This spider diagram illustrates the score (on a scale of 0–1) for all

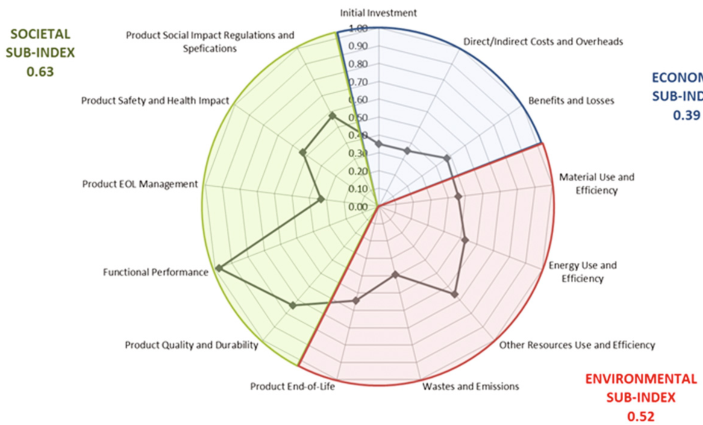

Fig. 2. Cluster-based calculated *ProdSI* for a product [12]

13 clusters, and shows the sub-indices for economy, environment and society. This ultimately leads to a *ProdSI* score of 0.51 (with equal weightage for sub-indices) indicating a slightly better than average product sustainability. This method can be applied to compare sustainability performance of a single product over a period of time or products from different generations to assess the impact of progressive design changes, and to compare similar products from competitive manufacturers [12].

Unlike most previous approaches that are biased towards only economic and environmental assessment, the *ProdSI* method provides a comprehensive evaluation of product sustainability performance by considering all relevant aspects.

3 Sustainable Product Design/Development Process

Early design considerations can significantly reduce a product's manufacturing cost. Many aspects that influence the product sustainability, eventually providing significant cost savings, improved environmental impact with societal benefits can also be established in the early product design stage. For example, the materials and resources such as energy and water used in manufacturing processes to fabricate components, as well as in all other related activities, including assembly, will all influence the overall product sustainability. Thus, while the *ProdSI* method is a comprehensive evaluation approach, that alone is not sufficient in the quest to enhancing product sustainability. It is imperative that key criteria that influence total life-cycle product sustainability performance are identified and considered during the product design process to ensure that product sustainability is enhanced during pre-manufacturing, manufacturing, use and post-use stages [13].

A new framework for such a sustainable product design/development process is illustrated in Fig. 3. As shown, initially during concept development, the design team requires better guidelines to assist selecting product/component features that meet customer requirements while also enhancing total life-cycle sustainability. Such guidelines could be developed, for example, by promoting the selection of material/process alternatives that enhance the *ProdSI* score (by positively influencing the various metrics, sub-clusters and clusters). However, product parameters are also highly interdependent [14, 15] and trade-offs among them can positively or negatively affect the overall performance of products/components, including life, durability, upgradability/maintainability, repairability, reusability, remanufacturability, etc.

With rapidly growing advanced manufacturing processes such as additive manufacturing where a product's complex geometric requirements can be achieved with significant savings of materials/resources used, an important area that is inadequately addressed is the *functional performance of manufactured components*. This functional performance needs to be considered at the product design stage with targeted *functionality, product life, performance and maintenance issues.* Therefore, during the detailed design, prototype development and testing stages, product designers will require predictive performance models to develop optimal product designs considering various trade-offs. Such decision support tools can be used to maximize/minimize the product's specific objectives, incorporate constraints, and conduct sensitivity analyses to assess the influence of different product design variables.

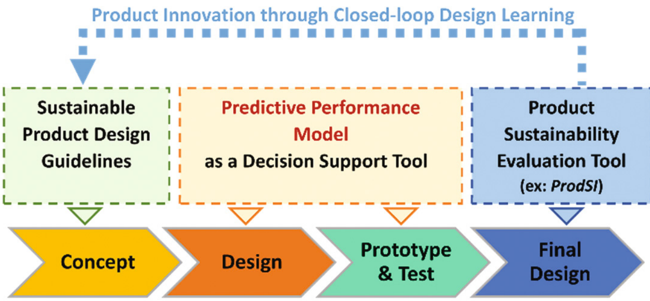

Fig. 3. Sustainable product design/development process (adapted from [13])

Once the *optimal design* is selected with support from *predictive performance models,* during the final design stage, product sustainability evaluation tools, such as *ProdSI*, can be used to evaluate the total life-cycle sustainability. The iterative application of the product development process outlined in Fig. 3 can enable designers to continuously innovate and develop successively better product designs. This approach helps identify and incorporate product sustainability drivers to enhance TBL performance, total life-cycle coverage and multi life-cycle material flow early during the design process. By incorporating predictive models for optimal product design, sustainable value is created for all stakeholders.

4 Predictive Performance Models for Sustainable Products

4.1 Significance of Predictive Product Performance Modeling

Significant progress is being made in evaluating the quality, performance and life of production equipment and machines. The need for designing and developing components used in such production equipment and machines for enhanced product performance and life is emerging as an important area of research focus.

Increasingly complex products are designed and developed to satisfy the growing functional needs. However, the anticipated functional requirements are largely feature-based, and are aimed at meeting the immediate need for functionality with quality and cost considerations and marketability, mostly with no long-term performance projections, and with very little consideration on upgradability and maintainability. Sustainability characteristics such as reusability, recyclability and remanufacturability are gaining significance in recent years with research focus on material selection, use and post-use activities. Developing lightweight designs for improved energy efficiency and performance in numerous products is another research focus area that is also closely tied to cost reduction.

Additive manufacturing provides tremendous opportunities for producing complex features in components to satisfy multiple functions with light-weight options. However, at the design stage when deciding between such alternative processes, the long-term functional performance requirements, including sustainability characteristics are important aspects to consider [13]. Predictive product performance models, therefore, are essential to help evaluate alternate product designs for their functionality, cost, quality and other sustainability characteristics over the duration over which the particular product could be in market.

4.2 Component Level Performance Needs

Product – Process integration with multi-level production systems involving component and machine level interactions is shown in Fig. 4 [16]. As seen, in a multi-level interactive production environment, the components produced become a part of an assembled, and significantly more complex, product, which in function is similar to a machine on the shop floor as it is an assembled product. Such components, whether assembled or stand-alone, are expected to perform to satisfy the functional needs. Product design for performance therefore must include predictive performance characteristics such as projected life, wear and tear rate including quality/performance deterioration rates, maintenance requirements, etc. Material and process selection for manufacturing these components is also a major responsibility of product designers.

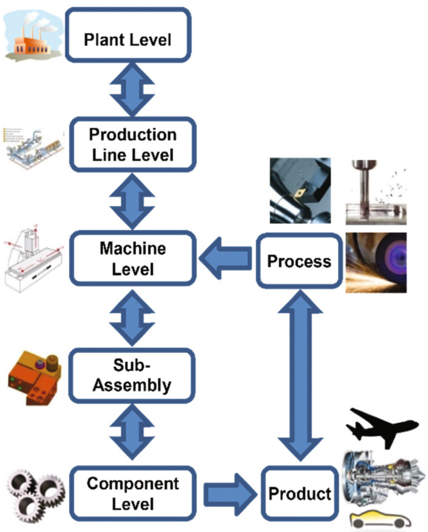

Fig. 4. Product – Process integration with interactions of multi-level production elements [16]

4.3 Product Design for Sustainability

Figure 5 shows the potential impacts of 6Rs on the previously established 13 product sustainability clusters, emphasizing tangible environmental and societal benefits and economic gains feasible. A review of the multiple sub-clusters and metrics associated with each cluster (see [12] for details) enables identifying the potential benefits of 6R

Clusters / 6R Elements	Product Sustainability												
	Economy			Environment					Society				
	Initial investment	Direct/indirect costs & overheads	Benefits & losses	Material use & efficiency	Energy use & efficiency	Other resources use & efficiency	Waste & emissions	Product EoL	Product quality & durability	Functional performance	Product EoL management	Product safety & health impact	Product societal impact regulations & certification
Reduce	x	x	x	x	x	x	x	x			x	x	x
Reuse	x		x	x	x	x	x	x			x		
Recycle			x	x			x	x			x		x
Recover				x			x	x			x		x
Redesign		x		x	x	x	x	x	x	x	x	x	x
Remanufacture				x	x	x	x	x			x		

Fig. 5. 6R applications in product sustainability cluster areas

implementation illustrated in Fig. 5. A more detailed analysis can be performed when a comprehensive metrics-based evaluation is performed for product design improvement for achieving greater sustainability. Analytical predictive performance models discussed in the next section, too, will enable a more quantitative assessment of 6R impacts on product sustainability.

4.4 Integrated Product Performance Models and Optimized Product Design

When designing sustainable products, multiple project objectives emerge such as energy/resource efficiency during manufacturing, use and post-use stages, projected product life/durability, product upgradability and performance, product's EOL options, etc. These aspects need to be *modeled predictively* with sufficient reliability and confidence levels, including potential risks, to estimate the total life-cycle cost and to determine the performance targets. Conflicting objectives would often require trade-offs when designing and developing such models. Integration of predictive performance models and optimizing for desired objectives, within the imposed constraints, thus become critically important at the product design stage.

Figure 6 shows the proposed comprehensive sustainable product design process through predictive performance modeling. To implement such an optimized process, different product sustainability considerations such as environmental impact, resource efficiency and economy and product functionality and their variation over the total life-cycle (covering pre-manufacturing, manufacturing, use and post-use stages) must first be quantified through predictive performance models. For example, predictive models for energy efficiency, material/resource efficiency or total life-cycle cost will enable the analytical assessment of product design performance along these different aspects. To evaluate potential trade-offs among the many conflicting aspects, the individual models must be combined to develop *Integrated Predictive Performance Models*. The optimized sustainable product design can then be developed by following

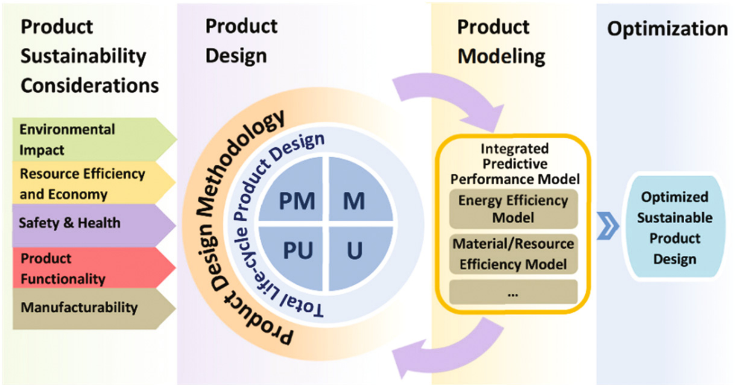

Fig. 6. Proposed optimized sustainable product design process

an iterative process. The integrated predictive performance models can be used to identify a product design through optimization, evaluate its sustainability performance using tools such as the *ProdSI,* and iteratively change product features/attributes until the final optimized sustainable product design that maximizes overall product sustainability performance is determined.

5 Summary and Outlook

Since major decisions impacting the product performance and life are made during the product development stage, it is essential to have sustainability considerations as input parameters for the product development process, along with the conventional customer and production requirements. Sustainability considerations themselves are interdependent, and also interact with the customer and production requirements, adding to the complexity of sustainable product development process. Thus, an integrated product performance model and optimization process would be required to maximize the overall product performance and sustainability. The work presented in this paper is the initial step towards developing a comprehensive optimized sustainable product design process incorporating predictive performance modeling.

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