Journal of Cleaner Production xxx (2015) 1–11

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

A unit process model based methodology to assist product sustainability assessment during design for manufacturing

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A R T I C L E I N F O

Article history:
Received 18 April 2014
Received in revised form
28 July 2015
Accepted 26 August 2015
Available online xxx

Keywords:
Product sustainability assessment
Design for manufacturing
Unit process model

A B S T R A C T

As the growth in demand for sustainable manufacturing continues, companies must begin to make conscious decisions with regard to the sustainability of their products. Thus, design and manufacturing engineers must consider economic, environmental, and social aspects simultaneously when developing products and process flows. The purpose of this research is to develop a sustainable assessment methodology to both improve the accuracy of existing approaches in identifying the sustainability impacts of a product and to assist manufacturing decision makers. The methodology developed utilizes unit process modeling and life cycle inventory techniques. Combining these approaches allows for conducting product sustainability assessment at the process level by quantifying a selected set of sustainability metrics. A demonstration of the methodology to assess three design alternatives for a bevel gear is presented. The developed methodology is capable of quantifying the sustainability metrics by aggregating information from the process level. It was found that the various metrics require different aggregation methods from the manufacturing process to the manufacturing system level. The general approach can be applied to aid the investigation of tradeoffs during the design decision making process for a wide range of products.

1. Introduction

The product manufacturing industry is starting to incorporate economic, environmental, and social aspects of sustainability into design decision making processes. The degradation of the environment caused by economic advancement led to the discussion of the notion of sustainable development on an international level at the 1992 United Nations Conference on Environment and Development. The conference covered several issues including the growing scarcity of water, the depletion of non-renewable sources of energy, and human health problems in the workplace and the community (United Nations Conference on Environment and Development, 1992). A major contributor to these issues was found to be the unsustainable production patterns in industry. The conference resulted in creating three major agreements including Agenda 21, The Rio Declaration on Environment and Development, and The Statement of Forest Principles (United Nations Conference on Environment and Development, 1992). These agreements comprise of a program of action and a series of principles to address all areas of sustainable development.

In the United States, regulations are documented within the US Code of Federal Regulations (Code of Federal Regulations, 2014), and includes regulations such as the Clean Air Act, the Clean Water Act, and the Resource Conservation and Recovery Act. The United States Environmental Protection Agency (EPA) enforces these regulations to ensure the protection of human health and the environment (United States Environmental Protection Agency, 2014). Regulations have forced companies to face the challenge of balancing economics with environmental and social aspects. It is a difficult task to reduce energy and natural resource consumption and ensure the well-being of employees, customers, and the community, all the while remaining economically competitive.

As consumers are becoming aware of sustainability in a broad sense, they are placing value on economic, environmental, and social responsibility. Thus, they are generating demand for more sustainable products and practices. Retailers are recognizing the cost benefits of reducing material consumption and eliminating wastes, and are demanding it from their suppliers. In some instances, retailers are requiring documentation from their suppliers

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http://dx.doi.org/10.1016/j.jclepro.2015.08.105
0959-6526/

Nomenclature

c_c	consumables cost
c_e	electrical energy cost
c_L	labor cost
GWP_{CH_4}	CH_4 global warming potential
GWP_{NO_2}	NO_2 global warming potential
m_c	mass of a consumable item
m_r	mass of material removed
P_i	idle power
P_m	motor power
P_s	standby power
r_{CH_4}	CH_4 generation rate
r_{CO_2}	CO_2 generation rate
r_{ill}	illness incident rate
r_{inj}	injury incident rate
r_{land}	fraction of waste sent to landfill
r_{lwd}	lost work day rate
r_{NO_2}	NO_2 generation rate
r_{NO_x}	NO_x generation rate
r_{rec}	fraction of waste sent to recycling
r_{SO_x}	SO_x generation rate
r_w	input water flow rate
r_{wd}	output water discharge rate
t_c	cycle time
t_i	idle time
t_m	machining time
t_p	process time
t_{ref}	time between tank refills
t_s	standby time
t_w	water flow time
V_f	final part volume
V_{haz}	volume of hazardous waste
V_i	initial part volume
V_s	stock material volume
ρ_{haz}	density of hazardous waste

to reduce energy use, greenhouse gas (GHG) emissions, and wastes (Sweeney, Oct. 2010). The trend of implementing sustainability goals continues to grow as companies experience these pressures from their customers.

In order to quantify the sustainability performance of a manufactured product, the economic, environmental, and social aspects must be simultaneously considered. When assessing the sustainability of a product, one must define the goal and scope of the study, select and quantify applicable sustainability metrics, identify the key unit manufacturing processes, develop mathematical unit process models to quantify the sustainability metrics, and analyze and interpret the results. This is a challenging set of tasks due to the extent of sustainability aspects to consider. According to Chiu and Kremer (2011), a majority of research and tools to assess the sustainability performance of a manufactured product at the design and process level focus just on the environmental aspect, and mathematical models to assess all aspects of sustainability are non-existent.

The objective of this work is to develop a product sustainability assessment methodology to improve the accuracy of quantifying metrics related to the economy, environment, and society during the design for manufacturing process. The six-step methodology developed as part of this research utilizes unit process modeling and life cycle inventory (LCI) approaches to quantify sustainability metrics for cradle-to-gate product sustainability assessment. It can be applied to assess the sustainability performance of alternative product designs from the process level. In the discussion below, current sustainability assessment approaches are first presented including metrics/indicators, life cycle inventory methods, and unit process modeling. Second, the six-step sustainability assessment methodology developed is explained in detail. Third, the methodology is demonstrated for design and manufacturing alternatives using a bevel gear manufacturing case study. Finally, the results of the case study and the conclusions discovered from this research are discussed.

2. Background

Sustainable manufacturing is defined by Haapala et al. (2011) as the "manufacturing of products that address sustainability goals in their use (e.g., renewable energy and green building products), as well as sustainable manufacturing processes and systems for all products." In order to achieve sustainability, decision makers must take into consideration the entire life cycle of a product and identify the impacts on the economy, environment, and society. Each decision that is made has implications for each aspect of sustainability and affects the present and future generations (Lozano, Nov. 2008).

2.1. Sustainability metrics

When conducting a sustainability assessment, one of the initial tasks is to define quantifiable metrics. The most commonly used sustainability metrics in practice are categorized into the three basic sustainability domains: economic, environmental, and social (Seager, 2004). The purpose of applying sustainability metrics to assess a product is to both measure sustainability performance and drive the advancement toward sustainability goals (Ranganathan, May 1998).

In a majority of applications, economic metrics are represented in terms of dollars. They are a measure of the capital incurred throughout a product's life cycle, and should reflect the impacts on the local, regional, and national level. Environmental metrics primarily focus on the impacts made by negative changes to the natural environment. They target the impacts on the land, air, water, and public health (Seager, 2004). In general, it is necessary to measure the efficient use of production inputs (materials, energy, and water resources) and the fate of outputs (emissions, effluents, and wastes). It is often uncertain how to best measure social metrics, which is primarily due to varying perceptions of social impacts and the mix between qualitative and quantitative measurements (Jørgensen et al., Dec. 2007). Developing social metrics is a challenging task, but necessary to bring awareness to design and manufacturing engineers of the social implications of their work and decisions.

The purpose of sustainability metrics is to measure the status or performance of a product relative to a particular category (Rachuri et al., 2009). Measurable, useful, and meaningful metrics will be relevant, understandable, manageable, reliable, cost-effective, and flexible (Feng et al., 2010). It is important to note that the measurement of the metric values should be used to guide for interpretation of sustainability performance. Furthermore, overall sustainability performance assessment must take into account all of the metrics simultaneously.

Standardizing metrics is required in order to compare the sustainability performance of different products. Utilizing publicly available metric sets is a beneficial way of accomplishing this task. Currently available metric sets range from a high level for corporate metrics to the individual product level. By far, most metric sets report the sustainability at the company level. Example company

Please cite this article in press as: Eastwood, M.D., Haapala, K.R., A unit process model based methodology to assist product sustainability assessment during design for manufacturing, Journal of Cleaner Production (2015), http://dx.doi.org/10.1016/j.jclepro.2015.08.105