Journal of Cleaner Production 139 (2016) 986–1000

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Terminology to support manufacturing process characterization and assessment for sustainable production

Ian C. Garretson [a], Mahesh Mani [b], Swee Leong [b], Kevin W. Lyons [b], Karl R. Haapala [a,*]

[a] Industrial Sustainability Laboratory, School of Mechanical, Industrial, and Manufacturing Engineering, Oregon State University, Corvallis, OR 97331, USA
[b] Systems Integration Division, National Institute of Standards and Technology, Gaithersburg, MD 20899, USA

A R T I C L E I N F O

Article history:
Received 5 December 2014
Received in revised form
29 July 2016
Accepted 21 August 2016
Available online 27 August 2016

Keywords:
Process characterization
Terminology
Sustainable production
Process modeling
Unit manufacturing process
Manufacturing

A B S T R A C T

Common terminology is essential for accurate communication among researchers, scientists, engineers, and other decision makers. To assist manufacturing process characterization, a common understanding of terminology is imperative for efficient and effective communication in industry; it can also facilitate automation and interoperability of software tools. Manufacturing process characterization enables the assessment and improvement of unit manufacturing processes, products, and systems from a sustainability perspective. To develop and implement sustainability-related standards and best practices in industry, naming conventions and definitions of common terms are needed. Presently, many terms used are ill-defined, vague, or overlap in meaning. Although there are ongoing standards efforts related to terminology identification and definition, an identified common set is yet to be developed.

The objective of this work was to facilitate ongoing standards development efforts by harmonizing the varied array of terms used to describe production processes. As a result of a review of the literature, a concise set of 47 terms focusing on process characterization and able to describe sustainable production was generated; terms unique to individual production processes were omitted. The terms were organized into six categories to define the overarching concepts: Scope, Boundary, Material, Measurement, Model, and Flow. Definitions of the terms were then derived from the literature in sustainable manufacturing and chemical and process industries, process characterization and planning, organization standards, and life cycle assessment and management.

The reported terms and definitions are not unique to sustainable production, and could foster widespread use of the concepts to improve the economic, environmental, and social performance of industry. In the future, the terminology described could be standardized through international standards organizations. Further, a rigorous review of research on manufacturing process characterization and process modeling in support of sustainable production is yet to be accomplished. Such a review would aid in organizing prior work by process type, perhaps by using a standard process taxonomy. Thus, a generalized, industry-relevant method for manufacturing process characterization could emerge to support sustainability assessment, and could be implemented through software applications accessible to a variety of users.

1. Introduction

Production is often the source of many environmental and ecological impacts, making it a focus of sustainability-related research, reports, and legislation. Environmental legislation began to appear in the U.S. in the late 1940s with the Water Pollution Control Act (1948). In the 1960s the Clean Air Act (1963) was followed by National Environmental Policy Act (1969), which legislated the enforcement of early sustainability policies. Soon after, in 1970, Environmental Protection Agency (EPA) came into being (Richardson and Wood, 2006). Similar laws were enacted globally in the same time frame, e.g., Japan's Pollution Diet (1970), and similar agencies were created, e.g., West Germany's Federal Environmental Agency (1971) (Richardson and Wood, 2006). International efforts arose as meetings and subsequent reports, e.g., UN Conference on Human Environment (1972), the Brundtland report (1987), Earth Summit in Rio (1992), and Agenda 21 (1992). The Brundtland report (1987) was especially significant since it

* Corresponding author.
E-mail address: karl.haapala@oregonstate.edu (K.R. Haapala).

http://dx.doi.org/10.1016/j.jclepro.2016.08.103

proposed a definition for sustainable development as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs."

Elkington (1997) posited that businesses must consider both natural and social capital, along with economic capital, in their management plans to achieve a positive triple bottom line (people, profit, and planet). Thus, the Brundtland definition was expanded to include multiple dimension, and was adapted by Dyllick and Hockerts (2002) to address corporate sustainability as "meeting the needs of a firm's direct and indirect stakeholders (such as shareholders, employees, clients, pressure groups, and communities), without compromising its ability to meet the needs of future stakeholders as well."

The new century saw a change in the use of *sustainability* as a noun to *sustainable* as an adjective, indicating a conceptual shift in thinking of sustainability as an end goal to sustainability as an attribute of industrial products, systems, and practices. Sustainable design, as an engineering function within industry, for example, was expressed as "the design of human and industrial systems to ensure that humankind's use of natural resources and cycles do not lead to diminished quality of life due either to losses in future economic opportunities or to adverse impacts on social conditions, human health and the environment" by Mihelcic et al. (2003). Sustainable manufacturing was defined decade later by the U.S. Department of Commerce (DOC) (2013) as "creation of a manufactured product with processes that have minimal negative impact on the environment, conserve energy and natural resources, are safe for employees and communities, and are economically sound." These two definitions reflect the ideas earlier presented in the Brundtland report and by Elkington. Both definitions assert that there are negative environmental, economic, and social impacts related to the production industry that must be reduced to sustain and support the development of global civilization.

As a first step toward reducing such negative impacts, many companies have developed sustainability metrics and indicators that quantify the economic, environmental, and social performance of business practices (Feng and Joung, 2011). To quantify sustainability performance, life cycle assessment (LCA) methods, which have been implemented in numerous software tools, are commonly used. However, these methods are often opaque, costly, and time consuming; while existing tools can provide performance assessments, they offer little guidance for performance improvement. Reap et al. (2008a, 2008b) reported that challenges arise due to information about and use of the functional unit (Section 4.6.1), in addition to system boundary definitions, allocation and flow analysis, and the subjectivity introduced by aggregation of impact data.

To address these problems, more comprehensive, sustainable product design methods have been developed, e.g., Chiu and Kremer, 2011; Ramani et al., 2010, but these often omit detailed evaluation of production process and system performance. Unit manufacturing process (UMP) characterization can be used to assist detailed production system assessments, and thus fill this gap. UMP modeling and development of cost effective, environmentally friendly UMPs were identified by the National Research Council (NRC) (1995) as two key areas for engineering research and innovation. A generalized UMP characterization method was subsequently demonstrated using specific case studies, e.g., Dahmus and Gutowski, 2004; Jiménez-González et al., 2000; Murphy et al., 2003, and was developed more recently into defined methods, e.g., Eastwood and Haapala, 2015; Kellens et al., 2012a, 2012b; Overcash and Twomey, 2012. Unique case studies are still being published, e.g., Dornfeld and Linke, 2012, to support methodological development efforts.

In sum, in today's competitive global market, manufacturers are being compelled to create and deliver high quality products in a cost effective and socially responsible manner, while reducing the environmental impacts of their activities. Thus, a key challenge lies in effectively quantifying and communicating sustainability performance of UMPs to facilitate improvement decisions. Current industry practices to compute sustainability performance are not standardized. Consequently, these practices rely on *ad hoc* information and non-uniform methods to calculate the performance of production processes and equipment. There is growing interest from industry, government agencies, and standards development organizations to change this situation by developing sustainability-related standard guides to facilitate such communication and decision making.

One such effort is being pursued by ASTM International (2016, 2014). The scope of the ASTM sustainable manufacturing standards (currently in the form of work items) addresses the evaluation aspects, terminology, characterization of manufacturing processes, and classification of waste at manufacturing facilities. The guides currently being developed are envisioned to assist manufacturers in characterizing manufacturing processes for sustainability and to support relevant decision making. Transferring sustainability-related standards and guides to the industry, however, requires a common language (terminology and definitions). Presently, many terms used in the area of sustainable manufacturing are ill-defined, vague, or overlap in meaning. Although there are ongoing terminology-related standards efforts, including those undertaken by ASTM, an identified common set of terms and definitions is yet to be developed.

Thus, the objective of this paper is to define standardized language for UMP characterization that can be used to support sustainability assessment of products, production processes, and production systems. Detailed UMP characterization can be used as a component of bottom-up analysis approaches to conduct product sustainability assessments. Because an overarching aim is to enable broadly usable sustainable production assessments, the terminology is identified primarily from sustainable-production and life-cycle-assessment literature. This literature was selected to ensure definitions appropriate to the contextual domain under study. Many of the terms have commonly accepted definitions, which are included here for completeness. While we recognize the need for supporting ontologies and methods for UMP characterization, addressing that need is beyond the scope of this paper.

2. Method for terminology definition

Seuring and Müller (2008) reported that literature reviews accomplish two objectives: "first, they summarize existing research by identifying patterns, themes and issues. Second, this helps to identify the conceptual content of the field and can contribute to theory development." From this viewpoint, the goals of the literature review herein are 1) to summarize the language and concepts used in UMP characterization for sustainability assessment and 2) to enable the development of supporting theory, methods, and industrially-relevant tools. Themes from the field will arise as a consequence of this goal. Beruvides and Omachonu (2001) described a ten-step process that is adapted to assist in the literature review. The first three steps (1–3) of their process direct the early stages of the literature search. The next four steps (4–7) describe article organization. The eighth step (8) analyzes the data and content using several methods. The next two steps (9–10) address the identified gaps, reporting, and actions. The steps undertaken in the literature review presented here modifies this approach as follows:

1. Review literature to identify relevant areas for terminology search