Sustainable Materials and Technologies 1–2 (2014) 17–25

Contents lists available at ScienceDirect

Sustainable Materials and Technologies

A framework for identifying performance targets for sustainable nanomaterials

Robert I. MacCuspie [a,*], Harvey Hyman [b], Chris Yakymyshyn [a], Sesha S. Srinivasan [b], Jaspreet Dhau [a], Christina Drake [a]

[a] College of Engineering, Florida Polytechnic University, 4700 Research Way, Lakeland, FL 33805-8531, USA
[b] College of Innovation & Technology, Florida Polytechnic University, 4700 Research Way, Lakeland, FL 33805-8531, USA

ARTICLE INFO

Article history:
Received 16 September 2014
Received in revised form 30 October 2014
Accepted 13 November 2014
Available online 27 November 2014

ABSTRACT

An issue in the application of nano-enabled products is how can we evaluate sustainable solutions to current system problems based on performance criteria? This work describes the application of an Input–Process–Output (IPO) model as a framework for a life-cycle analysis approach to identify performance metrics and criteria for evaluating the application of nanomaterials to improve the sustainability of a system. A case study is presented describing a scenario whereby a nano-enabled biocidal paint is considered for a remediation effort to reduce growth of dark molds and bacteria on refrigerated warehouses. The framework is applied to support identification of the energy-consuming steps (such as increased refrigeration energy burden, cleaning and repainting), selection of performance metrics for evaluating consumption, and determination of thresholds to measure sustainability outcomes.

1. Introduction

Sustainability is a term that encompasses a broad range of goals. In recent years, a focus has emerged on identifying ways of increasing sustainability [10]. Examples include studies of sustainable materials for buildings in specific cities [2], materials selection for developing sustainable products [20] or automotive applications [7]. However, quantitative metrics of sustainability often depend upon the case being considered and the goals. Examples of goals could include decreasing energy consumption, decreasing water consumption, or generating less hazardous waste, with corresponding quantitative metrics of metered kWh consumption, metered water consumption and gallons of hazardous waste, respectively.

The costs and benefits of each of these metrics can vary depending upon the location of the system. For example, in California and Arizona supplies of fresh water are scarcer than in the Northeast. Similarly, the energy generation portfolio varies from state to state. If carbon emissions from electricity generation are a desired quantitative metric, this is related to metered kWh consumption. However, the correlation between those two metrics will be of relatively higher or lower concern depending upon the location within the country. For example, natural gas is used to generate the majority of electricity in Florida, while hydroelectric generation dominates Washington state [33].

The broad range of potential metrics by which to assess sustainability creates a range of decisions for researchers seeking to develop new materials that provide sustainability solutions. Identification of useful and measurable metrics, and meaningful targets for these metrics, is a requirement for defining success. In complex systems many of these metrics can have dependencies upon one another that must be considered. Therefore, this work aims to present a framework for identifying material performance targets and metrics in the context of analyzing system sustainability performance improvements, illustrating this framework with an example of how this applies to nano-enabled sustainable materials.

2. System, lifecycle, process and process modeling

For purposes of this work, a *system* is defined as a collection of people, products, technology and tools organized in a particular way. In this discussion, *lifecycle* is defined to be a representational model of stages in a process that has a beginning, defined stages in the middle, and an end — a cradle to a grave. Within a lifecycle, stages can proceed in a loop back towards beginning earlier stages, or proceed towards the end. A system can be modeled as a lifecycle, and a lifecycle can be modeled as a process.

A *process* is defined as a collection of activities organized in such a way as to produce a result. The result is tied to a specified goal or objective of the system. The system itself is described in a graphical or narrative model intended to express its characteristics in a way that that is easily understood by others not familiar with the system. Once a goal or objective of the system is established, a method for achieving that goal or objective can be specified. The model describes the methods and applications used to produce the result (goal to be achieved), inputs

* Corresponding author.
E-mail address: rmaccuspie@flpoly.org (R.I. MacCuspie).

http://dx.doi.org/10.1016/j.susmat.2014.11.003

required, and the process for transforming inputs to outputs. In this paper a one-way direction in the process is assumed.

We apply an IPO (Input–Process–Output) model to classify the stages of the process and explain the system lifecycle described in this framework. The IPO model has particular advantages that make it an attractive tool to apply to a system oriented problem set. First, IPO provides a structured approach for identifying goals and objectives of a system as outputs and how those outputs might be measured to evaluate choices in process methods. Second, the structured approach of IPO supports a gap analysis for selecting what inputs are required to achieve which outputs.

In this case, the primary goal of the system is improved sustainability. Using an IPO framework in a case such as this allows decision makers, who may lack necessary technical expertise in specific process and method selections, to view the entire system as a black box and apply a lifecycle approach to assess alternative proposed treatment plans. From the lifecycle analysis point of view, where we are focused on the goal of sustainability as evaluated in terms of costs of system *inputs* and benefits of system *outputs* to assess choices of methods in the *process*.

As a support tool, the IPO model (Fig. 1) has been in existence for quite some time, and has been used to describe both theoretical and existent systems primarily in the fields of business process modeling and data analytics. It has been used to explain characteristics in technology systems [15], measure success factors in project management [31], predict user acceptance in information systems [8], and describe team characteristics in new product development [30]. This paper describes how the IPO model can be applied as an evaluative tool for the domain of sustainability in materials and technology.

The IPO model represents a system in three stages: input, process and output. Inputs are modeled as consumables and efforts that are introduced to a system at the beginning stage of the lifecycle. Outputs are modeled as the result produced by the system. Process is modeled as the conversion of the inputs to the outputs.

To illustrate how this framework can be implemented, a model system case study will be presented. The scenario is as follows. A refrigerated warehouse, painted white, is susceptible to mold growth. When mold grows, the exterior color of the building darkens and thus increases the electricity consumption due to the greater cooling burden. In order to decrease cooling energy consumption, the warehouse building is pressure washed to clean the dark mold from the building. As a potential sustainability solution to reduce the frequency of pressure washing, a biocidal paint could be applied. Therefore, the following questions must be answered: 1) what is the target biocidal performance required to result in a net increase in sustainability, and 2) what metrics should be used to define and measure that increase in sustainability?

In the case described in this paper, the IPO model is adapted to support identification of performance targets for sustainability metrics, using lifecycle stages identified in this use case of reducing mold growth through application of biocidal paint. This enables evaluating choices in materials applied and implementation methods performed to achieve the goal of the system: increased performance in sustainability. Applying the IPO model to assessing the sustainability of nano-enabled products is, to the knowledge of the authors, a novel application of the IPO model approach.

Fig. 2 illustrates the model process of a refrigerated warehouse. A warehouse, assumed to be initially a pristine painted white, requires a given energy consumption for cooling (E_{c1}). A generalized equation is shown in Fig. 2 for the variables to consider when calculating the energy consumption for cooling. Over an initial time, τ_1, contamination begins to build up, requiring a greater energy consumption for cooling (E_{c2}). Eventually, a heavy buildup causes the greatest energy consumption (E_{c3}) to be reached. At this point, the warehouse can either be pressure washed or repainted. The decision to pressure wash or repaint could be made based on whether the energy consumption (E_c) is below or above a threshold (E_{th}). Pressure washing would remove some, but not all, of the contamination, and would require an energy consumption for washing (E_{wash}) and material resources (M_{wash}). Repainting would return the building to the initial pristine surface, and require energy consumption (E_{paint}) and material resources (M_{paint}). Energy consumption and material resources should consider all aspects of the process of washing or repainting. For example, not only the energy to manufacture the paint and supplies used, but also if hazardous waste is generated the energy of disposing of the waste.

In the case of mold growing on the warehouse exterior surface, the darkened color and higher emissivity of the mold compared to the original white surface increases the cooling burden on the warehouse. The darker color of the mold decreases the amount of light reflected compared to the pristine white surface, thereby decreasing the surface albedo value (a) and increasing E_c.

Using Fig. 2 for guidance, one can model this use case using three separate processes that can be combined into a larger ecosystem lifecycle model, as summarized in Table 1. The first process is Dark Mold Growth. In this process, we model mold growth factors as the inputs, mold growth rate as the process, and the change in surface albedo over time as the output. Measureable consumables of the input could include factors such as availability of food and water sources, biocidal properties of the painted surface, and surface temperature. While the change in surface albedo is potentially a directly measurable unit of the output (or result produced), a more convenient measure is the kWh of energy consumed for cooling (E_c).

The second process is Pressure Washing. In this process, the energy required to perform the washing (E_{wash}) and the energy required to make the materials consumed in washing (M_{wash}) are the measurable consumables of input. The process is modeled as pressure washing, and albedo (or E_c) as the measureable unit of output (or result produced).

The third process is Repainting. In this process, E_{paint} and M_{paint}, the energy of repainting and making materials consumed in repainting, are modeled as the measureable consumable, repainting as the process, and return of albedo to the pristine value as the measureable unit of output (or result produced).

3. Selection of variables & data analysis

Once we complete the modeling of the system process, we next select measured variables (MVs) to represent the system outputs and system inputs. The corresponding outputs and inputs represent the choices in methods for the process being evaluated.

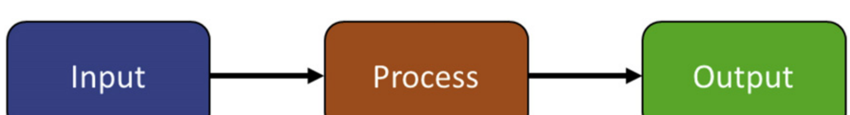

Fig. 1. The Input–Process–Output, or IPO, model.