A Framework for Identifying Sustainability Performance Targets for Nanomaterials

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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.

Keywords: NanoEHS, sustainability, life cycle analysis

1 INTRODUCTION

The idea of sustainability has been rapidly growing in recent years [1] and there has been a focal point on identifying new ways of increasing sustainability [2]. Examples include building materials for specific locations, material selection for sustainable products and applications for automobiles. There are many variables in sustainability, such as energy consumption, water consumption and generating less hazardous waste, all with an overall goal of reducing each as much as possible. These variables can have corresponding metrics such as metered kWh consumption, metered water consumption, and gallons of hazardous waste produced. Each of these metrics are dependent upon geographic location. For example, one might use fewer kWh when cooling a house in Ohio during the summer than if in Florida. Similarly, the water supply is scarce in places like Arizona and California when compared to the northwest. Depending on the location in the country, each of these variables will have a different weight that may affect the amount of consumption of each.

In this work, the IPO model is being applied for the concept of sustainability and the results of the model can be easily interpreted and thus decisions can be made with ease. For this work, a system is defined as a collection of people, products, technology and tools organized in a particular way. A process is defined as a collection of activities organized in a way that produces a result. Using the IPO model, we can classify the stages of the process and break it down to represent the stages within the model. We can also use it to monitor the process and the system's lifecycle described in the presented framework; one of the benefits of following the IPO model is that it provides a structured way to identify and measure the differences between outputs and the goals and objectives as a consequence.

To show how the IPO system can be implemented in this case study, the scenario is as follows: A refrigerated warehouse that has white exterior paint is susceptible to mold growth. As mold grows on the white walls they darken. This results in an increase of power consumption, due to the increased cooling burden of the warehouse. To reduce the cost of cooling, the warehouse is pressure washed to clean the darkened walls. A potential sustainability solution to reduce the amount of water consumed in pressure washing is by applying a biocidal paint to the walls. This raises two main questions: 1) What is the target biocidal performance required to result in a net increase of sustainability? 2) What variables should be used to define and measure that increased sustainability?

The IPO model was adopted to identify the performance targets for the sustainability metrics. This allows choices to be made about materials applied and the implementation of methods to achieve an increase in sustainability. The model can be broken down into three process that can be combined into a larger lifecycle model. They are summarized in Table 1. The first process is dark mold growth. In this process, the input is mold growth factors. Factors can be positive such as temperature and food, or negative such as the effects of biocidal paint. The process is the mold's growth rate. This results in an output of change in the surface albedo over time (in other words, darkening of the walls). The second process is pressure washing, with inputs of the amount of energy, water, and cost of materials it takes to pressure wash. After pressure washing the walls, there will be a removal of mold resulting in a change in albedo. The third process is repainting. In this process, the walls are being repainted and returning the albedo to its original and pristine condition. The input of the process requires the energy to repaint the walls and the cost of materials.

Table 1: Inputs, Processes, and Outputs

Description	Input	Process	Output
Dark mold growth	Mold growth factors	Mold growth rate	Change in surface albedo

Pressure washing	Energy and materials	Pressure washing	Measurable change in albedo
Repainting	Energy and materials	Repainting	Albedo returns to pristine

2 APPLIED MODEL

Sustainability = $BX_1 + BX_2 + BX_3 + BX_4 + BX_5 + BX_6 + BX_7 + BX_8 + BX_9 + BX_{10}$

This equation describes 10 examples of different variables that can affect the outcome of the sustainability of the refrigerated warehouse. The variables selected may not necessarily be the most important in every situation, however they are provided for illustrative purposes and are as follows:

- Air temp: X_1 = collected hourly
- Internal Temp: X_2 = target cooling temperature
- kWh: X_3 = hourly cooling energy consumption
- Mold growth rate: X_4 = daily average
- Humidity: X_5 = daily average
- Pressure washing water consumption: X_6 = Liters water used, yearly average
- M_{paint}: X_7 = kWh used to manufacture consumables used in repainting
- E_{paint}: X_8 = kWh used repainting
- E_{wash}: X_9 = kWh used pressure-washing
- M_{wash}: X_{10} = kWh used to manufacture consumables used in pressure washing.

It is safe to assume that if looking at a single warehouse, air temperature, internal temperature, mold growth rate, and humidity will not change on different parts of the unit. The only variables that will change (and therefore, affect the experiment), are hourly cooling energy consumption, pressure washing water consumption, energy used to manufacture consumables used in repainting, energy used to repaint, energy used to pressure wash, and energy used to manufacture consumables used in pressure washing. It is important to note that exterior surface area is a key factor that affects multitude of variables and will be talked about later in the paper, along with hourly cooling energy consumption and pressure washing water consumption.

In this data set, assumptions were made that:

- Only repainting returns surface to original pristine.
- Pressure washing does not clean all of dark mold and therefore increases exponentially over time.
- Esthetics impact repainting rate
- Arbitrary boundary condition of $E_{c'}/E_{c0} = 4$.
- The mold growth rate will be faster after each round of pressure washing.

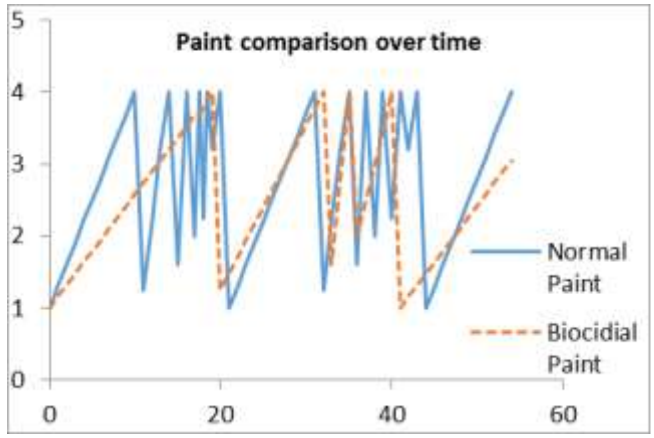

Figure 1: Nomralized Energy Consumption ($E_{c'}/E_{c0}$) vs time, with modeled data for normal paint and biocidial paint, including effects of pressure washing and repainting and mold growth rate.

The arbitrary number 4 for $E_{c'}/E_0$ was chosen just to quantify the threshold where a person cannot allow any more dark mold growth to occur and must either repaint or pressure wash. After each pressure wash, the time between each pressure washing decreases. After 6 pressure washes, a repainting job was deemed to be necessary for both normal paint and biocidial paint. Also, it took 2 worths of repainting with normal paint for every 1 worth of repainting with biocidial paint.

3 FRAMEWORK APPLICATION

In order to demonstrate how the framework can be used to create target performance metrics, assumptions can be made using data from existing literature to generate example data for our case study. Morales et. al reported the mean heated area for a Floridian warehouse is 30,114 ft^2 based on a sampling of 221 warehouses [3]. Assuming that the building has an aspect ratio of 2:1, the warehouse would be 122.7 ft by 245.4 ft. Assuming that the average height of a warehouse is 25 ft, the surface area of the roof and all four walls would be 48,519 ft^2. Recently reported strategies for calculating accurate heating and cooling [4] combined with data for cooling load [5, 6] shows that the majority of load contribution (47%) is due to the building enclosure: the roof, walls, windows, and ventilation systems. Based on this data and strategies for calculating cooling burden, a 12% increase is estimated for the contribution of dark mold growth to the overall cooling burden on the building.

The Rough Order of Magnitude (ROM) for the heating and cooling load of warehouses based in Orlando, Florida is calculated by converting the previously determined building surface area (48,519 ft^2) to kilowatt, kilojoules per second. For a warehouse with surface area of 48,519 ft^2, the heating load is approximately 515,272 Btu/h (151 kJ/s), using the conversion factor for the heating load of approximately 10.62 Btu/h/ft^2 [4]. For the same warehouse, the cooling load is approximately 460,930.5 Btu/h by combining the load of about 7.5 Btu/h/ft^2 and latent load of 2 Btu/h/ft^2

(approximately 135 kJ/s) [4]. If a 15% increase in cooling burden due to the exterior surface contribution is assumed from the cooling model, the cooling burden increases to 137.4 kJ/s. If biocidal nanoparticle formulated paint completely inhibits the dark mold growth on the exterior walls, this mitigates the 2.4 kJ/s energy consumption difference between the 132 kJ/s cooling load for the pristine building, and the 134.4 kJ/s cooling load for the mold covered building.

An additional sustainability metric considered is the water consumption during pressure washing. The total yearly water consumption (X_6) is calculated by multiplying the water consumption for each pressure wash (W_{pw}, L) by the annual frequency of pressure washing. Water consumption (W_{pw}) can be estimated from the exterior surface area of the building (A, ft^2), pressure washer flow rate (PW_{flow}, L/min), and pressure washer cleaning rate (PW_{rate}, ft^2/min), as shown in Eq. (2). An example pressure washer with a 15.4 L/min flow rate and an assumed work rate of 50 ft^2/min cleaning the model warehouse previously described would provide an estimated water consumption of 15,000 L (3962 gal). Using the hypothetical data from Figure 1 normal paint requires 14 pressure washings, compared to 6 pressure washings required by the biocidal paint. This equates to the maximum water conservation potential ($W_{pw\ max}$) of 120,000 L (31,700 gal) of water per biocidal paint repainting cycle.

$$W_{PW} = \frac{A \cdot PW_{flow}}{PW_{rate}} \quad (2)$$

Using these assumptions and calculations as an illustrative hypothetical example, a performance target of decreasing mold growth rates by a factor of 5 yields a savings of 2.4 kWh of energy consumption and 120,000 L of water consumption.

Now that performance targets for a given sustainability savings can been established, nanotechnologist and materials scientists can evaluate the net change in sustainability specific to the new material under consideration. This is necessary because the new material may require additional energy and water to manufacture, transport, maintain, or dispose of properly. Specific to example in this paper, one possible biocidal additive that can be introduced directly into the paint is silver nanoparticles (AgNPs), which act as an antimicrobial primarily through the release of silver ions and generation of reactive oxygen species [7, 8]. Another possible additive is a photoreactive form of TiO_2, which generates reactive oxygen species. An additional option is to add organic biocidal molecules to the paint. While all available options should be evaluated and considered for their impact on sustainability when this model is fully applied, here we have selected AgNPs as a rudimentary example for the process of identifying the areas that are most likely to impact the sustainability of the nanotechnology solution. Because many of the methods involved in this evaluation vary greatly, it is in appropriate to approximate hypothetical values, as they would be meaningless. Nevertheless, many methods can be identified for consideration, and in a specific application can be determined empirically.

It is important to first consider the potential environmental impact of AgNPs. A growing body of literature has studied the lifecycles and fate of AgNPs and their release into the environment [9]. The sustainability costs due to safety considerations can be grouped into energy ($E_{nanoEHS}$) and water ($W_{nanoEHS}$). While the energy consumed in manufacturing, transporting, and formulating the nanoparticles that are to be used in the paint will depend heavily upon the nanomaterial manufacturing process and the formulation process of the paint, the energy and water used in these processes must also be taken into account in the model. The process of acquiring and applying silver nanoparticles can be viewed as an independent IPO. In this IPO, the inputs are energy, water, the process is the fabrication, transportation, and mixing and the output is silver nanoparticles. While physical materials are input into this system, when considering the IPO model within the sustainability framework, the energy and water representative of the physical materials is a more appropriate input for the function. It is important to understand that physical materials and a physical process is still involved, but the IPO model illustrates the sustainability, not the physical process.

The net change in sustainability for this example therefore be a combination of the resources saved in using the nanomaterial solution and the resources used in applying the nanomaterial solution. The calculations will ultimately be used to compare against the sustainability performance target to test if the solution increases overall sustainability, relating to X_7 through measurement of the usage of paint in gallons and the marginal energy costs. Additionally, as the resulting waste stream of many nanofabrication processes produces hazardous waste, creating an energy burden on the process of adding AgNPs to a nano-enabled biocidal paint, which impacts the M_{paint} and X_7 variables. As a Minimum Inhibitory Concentration (MIC) of less than 3 ppm of colloidal silver nanoparticles was reported for 14 bacteria and 5 fungal species, this suggests that a concentration of 30 ppm nanoparticle loading should be adequate for the desired effect. In this IPO, the inputs biocidal paint, water, and a pressure washer. The process undertaken is the pressure washing of the building at less frequent intervals, due to the biocidal effect. Finally, the output of the model is to return the building's surface albedo to slightly above the original value.

Based on the discussed model, multiple complex tradeoffs between nano-enabled biocidal paint and can be analyzed. For example, if the goal is to decrease overall cooling burden and/or the number of pressure washes, performance targets for biocidal activity can be developed.

The assumption that the repaint times for biocidal and non-biocidal are the same should be considered. This does not entirely negate the increase in sustainability of the biocidal solution, as it is possible that despite more frequent paintings, the model returns to the non-biocidal paint model. It is possible if the non-biocidal paint allows longer times between repaints that this makes up for the gains in normal cooling, pressure washing energy, and pressure washing water costs. It is recommended that a study be conducted on the release rate of AgNPs from a painted surface, and the decrease in activity of the biocidal coating over time as AgNPs are removed. In this work, assumptions about warehouse size, cooling burden from cooling envelope, and pressure washer consumption rate all impact tradeoff relationships.

4 CONCLUSION

This work presents the IPO model as a method for determining performance targets for developing sustainability solutions that utilize nanomaterials. The sustainability costs that can be measured are examined using liner regression analysis, which enables the determination of the most important factors and of the required performance milestones to achieve various improvements in sustainability costs of processes. This work was demonstrated with the application of a refrigerated warehouse, which requires frequent cleaning from dark mold growth that increases cooling energy consumption. Future work could extend this method to be even more robust in analysis depth without requiring the time required to complete a full life cycle analysis.

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