Journal of Cleaner Production xxx (2016) 1–9

Contents lists available at ScienceDirect

Journal of Cleaner Production

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

Sustainability indicators for industrial ovens and assessment using Fuzzy set theory and Monte Carlo simulation

F. Pask [a, b, *], P. Lake [a], A. Yang [c], H. Tokos [d], J. Sadhukhan [b]

[a] 3M Centre, Cain Road, Bracknell, Berkshire, RG12 8HT, UK
[b] Centre for Environmental Strategy, University of Surrey, Guildford, GU2 7XH, UK
[c] Department of Engineering Science, University of Oxford, Oxford, OX1 3PJ, UK
[d] Department of Chemical and Process Engineering, University of Surrey, Guildford, GU2 7XH, UK

ARTICLE INFO

Article history:
Received 27 November 2015
Received in revised form
15 July 2016
Accepted 10 October 2016
Available online xxx

Keywords:
Sustainability indicators
Fuzzy set theory
Monte Carlo simulation
Industrial ovens
Manufacturing

ABSTRACT

Industrial ovens play a significant role in many manufacturing and process industries. Despite the desire to enhance sustainability throughout this sector, research looking to improve the sustainability of industrial ovens is in its infancy. This paper presents seven sustainability indicators to assess potential oven investment; these include system air flow, production efficiency, operating costs, quality, capital investment, toxicity and employment opportunity. The indicators are straightforward, can be scored with readily available data and have been weighted by industrial experts. A hybrid multi-criteria approach using Fuzzy set theory and Monte Carlo simulation has been developed to help evaluate the sustainability of alternative improvement options. The approach is required as previous methodologies only present desirability as a singular figure; and therefore decision makers are not provided with sufficient information on associated risk. The presented approach incorporates uncertainty throughout, and gives option desirability in terms of mean, standard deviation and variance. The risks using this method are better understood and can significantly aid industrial decision makers. The sustainability indicators and hybrid approach have been demonstrated using a case study in the manufacturing industry; to identify the most sustainable way to increase cure conversion within an oven. Amongst the three options: increasing oven size, increasing oven temperature and new product formulation, increasing oven temperature shows the highest desirability, while new product formulation though has a lower desirability has the highest certainty. Furthermore, a cumulative desirability distribution plot gives a basis to select option that is aligned with the business's risk strategy.

1. Introduction

Sustainable development concepts and practices are becoming increasingly common throughout the manufacturing industry, however research focused on increasing the sustainability of industrial ovens is still in its infancy. Ovens consume a sizeable portion of industrial energy (EERE, 2013), and significantly affect the performance capability and environmental impact of a manufacturing process. The three dimensions of sustainability can be applied to have specific relevance for industrial ovens. For example; environmental concern can result in pollution and waste. The ability to manufacture quality product affects economic performance, and employee's safety falls within the social dimension of sustainability. This research aims to enable cleaner and more responsible production in the manufacturing environment.

Sustainability indicators can be used to inform decisions and provide insight into complex issues by balancing the three sustainability dimensions (Kwatra et al., 2016). They can be used to compare differences between potential oven improvements, and therefore help to develop a sustainable industry. Application of indicators for technology assessment can be used in two ways; a) to assess the overall performance of a particular technology system, or b) to compare at least two technology systems. Indicators should be applied using 'fit for purpose' approach rather than making a generic set of indicators fit for all applications (Dewulf and Van Langenhove, 2005). Indicators can be quantitative or qualitative, and can fall within the categories of descriptive, performance or efficiency indicators (Hallstedt, 2015). A UN report (Nations, 2007)

* Corresponding author. 3M Centre, Cain Road, Bracknell, Berkshire, RG12 8HT, UK.
E-mail addresses: fpask@mmm.com, freddie.pask@gmail.com (F. Pask).

http://dx.doi.org/10.1016/j.jclepro.2016.10.038

Nomenclature

c	sustainability indicator
A	Alternation option
w	Weight factor
x	Score of indicator
n	Number of indicators
m	Number of alternative option
$f1, f2, f3$	Triangular fuzzy number
$\tilde{x}_{mn}$	Normalized score for each indicator
w_n	Weighted fuzzy number
$\tilde{c}_{mn}$	Normalized weighted score for each indicator
$\tilde{r}_{mn}$	Randomly generate number
D	Desirability

sets a number of guidelines when selecting appropriate indicators. In summary, they should be simple and informative and approaches should be uncomplicated and without a large number of sub sets. Indicators should be responsive to changes in the environment and related human activities. They should be clear, unambiguous and provide basis for comparison.

Environmental indicators may include greenhouse gas emission, energy consumption, renewability of resources, toxicity of emissions, re-use of materials, recoverability of waste materials and efficiency (Dewulf and Van Langenhove, 2005). Proposed economic indicators relevant to industrial ovens involve net sales, operational production costs, gross margin and overhead costs (Pannell and Glenn, 2000). And finally, social indicators tend to be toxicology or safety related (Al-Sharrah et al., 2007; 2010).

As well as identifying a suitable set of sustainability indicators, it is also important to analyze the indicator set with a method of multi-criteria analysis appropriate for that particular application. For instance, Tokos et al. (2012) were able to develop a methodology for integrated sustainability performance assessment specifically for processing industries. Multi-criteria analysis is used to aid decision making by gathering information on a variety of criteria, or indicators, to understand how multiple objectives can best be achieved. It enables for indicators with different units to be assessed alongside each other. Fuzzy set theory is a long established field within multi-criteria analysis which presents a way to deal with problems which had previously been unsolvable by traditional multi-criteria analysis. It deals with approximation rather than exact reasoning (Zadeh, 1965), allowing for uncertainty to be assessed rationally by associating a grade of desirability to quantitative and qualitative data (Begić and Afgan, 2007; Niekamp et al., 2015; Fu, 2008). Fuzzy optimization is seen to be more robust than crisp optimization with Pareto optimum analysis as no iterative steps are required (Tay et al., 2011).

Fuzzy indicator sets including both qualitative and quantitative indicators have more recently been demonstrated as a method to assess sustainability indicators (Mendoza and Prabhu, 2004; Ducey and Larson, 1999), by enabling objective decision making of indicators, which may themselves be subjective. Uncertainty can result from imprecise measurements, average or outdated data using proxies and incomplete data, approximations in modelling, normalisation and weighting (Sadhukhan et al., 2014) assessment and linguistic descriptors by experts and their assigned values, in case of qualitative indicators. Uncertainty in the assessment of sustainable development causes issues when trying to solve problems using conventional multi-criteria analysis. Probabilistic theory is based on classical set theory which is defined by yes or no statements, and requires hard thresholds. Whereas Fuzzy theory is based on multi-valued logic and relates to events which have no well-defined meaning, allowing for the fuzziness to describe a degree to which an event occurs (and soft thresholds) (Cornelissen et al., 2001). Fuzzy sets do not have to be in or out, but are rather given a degree of membership. Fuzzy methods are useful when assessing complex or ill-defined problems, and can therefore be very useful for sustainability indicators. Fuzzy indicator uncertainty is not due to error or randomness, but attributed to generality, ambiguity or vagueness.

Monte Carlo simulation is a sampling technique used for result generation that depends on parameters given from probability distributions. Studies have been conducted that utilize both Monte Carlo simulation and Fuzzy set theory to evaluate sustainability indicator sets (Sadeghi et al., 2010; Loyd, 2004). Monte Carlo simulation requires the generation of random values to input into the model, where the model variables have a known range (as determined from a distribution type) but uncertain values in a particular event. Model variables can be provided by the triangular distributions generated in Fuzzy set theory. This technique is commonly used as a way to incorporate uncertainty into quantified risk assessment. Additionally there are guidelines for uncertainty analysis using Monte Carlo simulation for estimation and mitigation of uncertainty during environmental impact assessment (IPCC, 2006).

Although there has been valuable research into improving different aspects of industrial ovens (Pask et al., 2014; Khatir et al., 2015; Miah et al., 2014; Pask et al., 2016), an indicator set to assess overall oven sustainability has not previously been developed. This research is to provide a specific set of sustainability indicators that can be used to inform investment decisions for oven improvement and therefore provide a useful tool for manufacturing and process industries. The indicators are designed so that two or more alternative options can be evaluated to prioritize investment to deliver a more sustainable oven. To achieve this, a method of multi-criteria analysis using Fuzzy set theory and Mont Carlo simulation has been developed which aims to assist decision makers by incorporating uncertainty into a final desirability level; thus providing information so that investments can be aligned with risk strategies. The applied methodology is an adaptation of previous approaches, and has been tailored to present findings in a way which is particularly useful for decision makers in the manufacturing and process industries. The indicator set and methodology have been demonstrated using an industrial case study.

2. Methodology

A set of sustainability indicators for industrial ovens is to be identified in Section 3. This section details a hybrid method of multiple criteria decision making using Fuzzy set theory and Monte Carlo simulation to analyze sustainability indicators. Fig. 1 outlines all important stages of the methodology, while the rest of this section details each step fully.

The methodology entails a multi-criteria decision analysis tool to identify a preferred option, A_m amongst m alternatives. The method evaluates alternative options through the use of indicators. Equation (1) displays the multi-criteria decision analysis matrix, where c_n is the sustainability indicator, x_{mn} is the indicator score, m is the number of alternative option, and n is the number of indicators. When using such an approach, the sustainability indicators and alternative options for system improvements should be defined by expert insights. The list should not be exhaustive; the indicators should be the most important ones without overlap between them and those that make a difference in the overall sustainability performances between options and thus help in the selection of the overall best option (Sadhukhan et al., 2014). The