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Design of experiments for global sensitivity analysis in life cycle assessment: The case of biodiesel in Vietnam

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ABSTRACT

Biodiesel has been widely proposed as an alternative to fossil fuels and its environmental impacts have been commonly assessed using life cycle assessment (LCA). However, the results of LCA can be affected by parameter uncertainties. The rigorous treatment of such uncertainties is thus essential to improve decision-making based on the LCA. In this work, the Latin hypercube design of experiments (DOE) approach is proposed for global sensitivity analysis in LCA. In this novel approach, the LCA input parameters are used as the factors for the experimental design. The LCA of biodiesel from different feedstocks, namely, jatropha, waste cooking oil (WCO), and fish oil (FO), under the current conditions in Vietnam was chosen as a test case. The LCA focuses on the global warming potential (GWP), photochemical ozone formation potential (POFP), acidification potential (AP), and eutrophication potential (EP) of the biodiesel system. These impact categories were then combined into an overall environmental impact (OEI) score using the analytic hierarchy process (AHP). The effect of changes in the LCA model parameters on the OEI was then observed through computational experiments using a Latin hypercube design. From the computational experiments, the input parameters significantly affecting the results of LCA were identified, and a proxy polynomial regression model was derived to enable global sensitivity analysis to be performed. The results show that agricultural yield, oil content of jatropha seed, transesterification yield, total transportation, and biodiesel blending fraction are the factors that have significant effects on the OEI of jatropha biodiesel; biodiesel blend fraction and total transportation are significant in the case of WCO diesel, while the only significant effect factor in FO biodiesel case is biodiesel blend fraction. Biodiesel blend fraction is the most significant parameter for all feedstocks.

1. Introduction

One of the key questions when an alternative fuel like biodiesel is proposed for adoption is: “Is it really more environment-friendly than petroleum?”. Environmental sustainability has received a great deal of attention in the literature as well in practice (Mani et al., 2016). An internationally standardized methodology to assess environmental impact of an entire system from “cradle-to-grave” is life cycle assessment (LCA). However, the result of LCA is dependent on the quality of the input data (Von Bahr and Steen, 2004).There is always some degree of uncertainty in the input data for LCA studies (Ciroth et al., 2004). Uncertainty of LCA can come from parameter uncertainties, model uncertainty, uncertainty due to choices, while variability may refer to spatial variability, temporal variability, and variability between objectives and resource (Huijbregts, 1998). For decision makers, quantifying the impacts of this uncertainty is an important aspect for determining the quality of the LCA (Heijungs and Huijbregts, 2004). It is necessary to reduce the vagueness of results that may arise from models with numerous input parameters (Fazeni et al., 2014). Thus, uncertainty analysis should be conducted to determine the effects of factors on the results, and identify model parameters that have a significant contribution to the overall environmental impact of a life cycle system (Yang et al., 2011). Such uncertainties can also be assessed in order to identify

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key issues for more rigorous data collection or sampling (Heijungs, 1996). Uncertainty analysis is a method to determine which factors have the major contribution to the variation and which factors do not have significant effects on the final result of analysis (Ortner et al., 2016). Including uncertainty in LCA has been a topic of active research since the 1990s (Heijungs, 2014), and various extensive and important works have been done on uncertainty of LCA (Lloyd and Ries, 2007), but a standardized methodology to treat uncertainties of LCA is still missing (Groen et al., 2014). Uncertainty analysis has been previously applied to address the uncertainty and variability in the LCA of biodiesel from waste cooking oil (Caldeira et al., 2016).

There are different analytic or numerical approaches that are used to assess the uncertainties in LCA (Lloyd and Ries, 2007; Groen et al., 2014). For computing aggregated uncertainties, LCA could be integrated with interval analysis (Chevalier and Le Teno, 1996), probabilistic methods (Kennedy et al., 1996) and fuzzy methods (Tan, 2008). The Monte Carlo method has been mainly used to treat the uncertainty in LCA (Ciroth et al., 2004). Peters (2007) described algorithms to reduce computational times for implementation of this method. The effects of individual sources of uncertainty could be also assessed through methods, such as sensitivity analysis and matrix perturbation analysis (Heijungs, 2010). In Heijungs (1996), the key issues analysis method was proposed for uncertainty analysis that was used as a guide to determine if further data collection effort to improve reliability is justifiable. Methods such as probabilistic, interval LCA and fuzzy LCA can give the total uncertainty, while local sensitivity analysis, as commonly practiced, is a procedure that assesses the effect of varying one factor at a time while other factors are kept constant; this type of analysis can be done analytically or numerically (Heijungs and Suh, 2002). On the other hand, interactions effects are not easily analyzed by these established methods. The studies of Heijungs (2002) and Rivera and Sutherland (2015) indicated that LCA may show strong non-linear sensitivities and the interaction effects in LCA.

Design of experiment (DOE) techniques are primarily used to design the conduct of experiments in the physical world and to statistically analyze the results in order to understand the relationship between experimental factors and the output of a process. They have also been proposed for design of different types of computational experiments (Morris, 1991; Giunta et al., 2003) and solution of optimization models (Tan et al., 2015). By treating the computations like physical processes, DOE could be used to design the "experiments" or combinations of input parameters in the LCA model. The LCA input parameters are treated as the factors in the DOE and then used to observe the effects on the LCA output. Thus, DOE could have advantage over other methods in uncertainty analysis in LCA. It is not only suitable for determining the uncertainties but also quantifying factor interdependence using a statistically rigorous framework, which is not easy revealed by other methods (Rivera and Sutherland, 2015). Using DOE can be an efficient means to reduce the number of simulations as compared to Monte Carlo (Heijungs and Lenzen, 2014). Furthermore, this approach can be used to derive low-order polynomial models which can serve as approximations of the true model, and also give clear insights about general effects of parameters on the outputs. Latin hypercube method uses points in the factor space to ensure sufficient degree of freedom (Tan et al., 2015) to estimate quadratic effects. When Latin hypercube is used as a technique for uncertainty and sensitivity analysis, it is typically easy to implement and it has efficient stratification across the range of each factor (Helton and Davis, 2003). Latin hypercube may have other advantages, such as providing the linear and quadratic effects of all factors as well as bilinear interaction (Ye, 1998). The results of Latin hypercube model in computational experiments could provide more information than local or one-at-a-time sensitivity analysis, especially by elucidating interactions or joint effects (Tan et al., 2015). There are two recent studies that have applied DOE to assess the effect of parameter uncertainties in LCA. Rivera and Sutherland (2015) used two-level factorial design to assess the effects of input parameters on model output. Wei et al. (2014) proposed Sobol indices for global sensitivity analysis of matrix-based LCA to address uncertainty at the factor level. In this study, Latin hypercube DOE approach is proposed to assess uncertainty in LCA via global sensitivity analysis.

There are many environmental impact categories that may be quantified by LCA. However, it is not easy to make the best choice between alternatives or scenarios when there is more than one criterion must be taken into account (Daniel et al., 2004). So, the LCA calculation needs to include a weighting and aggregation step (Hermann et al., 2007). However, these steps are categorized as optional steps (Prado et al., 2012). Incorporating these categories into an overall environmental impact (OEI) should make evaluation and comparison between these alternatives easier but this requires making judgements of the relative importance of each environmental impact (Myllyviita et al., 2012). The weight of each impact category may be assigned a numerical factor according to their relative importance and summed into a single value (Guinée, 2002). Various weighting and aggregation methods have been proposed and applied in LCA (Reap et al., 2008). Johnsen and Løkke (2013) made a comprehensive review of different weighting methods that could be divided into distance-to-target method (Seppälä and Hämäläinen, 2001), monetary valuation methods (Ahlroth et al., 2011), panel weighting methods (Soares et al., 2006). Multi-criteria decision analysis (MCDA) is one of the most accepted approaches for integration to LCA (Myllyviita et al., 2014). MCDA has been used to identify the weights for environmental impacts and aggregate the results of LCA studies (Tan, 2005). In this study, the analytic hierarchy process (AHP), a widely used method of MCDA (Gloria et al., 2007), was used to give the weight for each impact category. It was also used to aggregate impacts into sustainability index in study of Reza et al. (2011). AHP is a measurement method from pair-wise comparisons to derive priorities for alternatives where the preferences could be obtained from judgement of participants (Saaty, 1977). AHP could integrate the judgments of Vietnamese experts on biodiesel and environment who have knowledges about the specific conditions for biodiesel production and use in Vietnam. It could be conducted to determine the relative contribution of each impact category on overall environmental impact (Madu, 2012).

In this study, Latin hypercube sampling was applied to determine the effects of parameter uncertainties of input-parameters on the LCA of biodiesel from three kinds of feedstock, namely jatropha oil, fish oil (FO), and waste cooking oil (WCO), based on the conditions in Vietnam. The Vietnamese government has a policy to produce and develop biodiesel to replace fossil diesel through Decision No. 177/2007/QD-TTg (The Prime Minister of Vietnam, 2007). Biodiesel could be produced from vegetable oil or animal fat, such as soybean (Byun et al., 1995), palm (Crabbe et al., 2001), coconut (Kumar et al., 2010), sunflower (Granados et al., 2007), jatropha (Tiwari et al., 2007), animal fat or waste cooking oil (Ho et al., 2014) and even weeds like *Calotrophis gigantea* (Phoo et al., 2014). However, food security is a major concern when we choose the feedstock for biodiesel production (Razon, 2009). Thus, crops like jatropha and waste oil, such as waste cooking oil and discarded fish fat may be preferable (Khang et al., 2015).

2. Methodology

A combined approach of LCA, AHP and DOE was applied in this study. LCA was used to evaluate four environmental impact categories: Global warming potential (GWP), Photochemical Ozone Formation Potential (POFP), Acidification Potential (AP)