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A stochastic multi-criteria decision analysis for sustainable biomass crop selection

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ABSTRACT

Selecting the most sustainable biomass crop type for biofuel production is a multi-criteria decision-making (MCDM) problem involving various conflicting criteria. In this paper, we propose a unique stochastic analytical hierarchy process (AHP) that can handle uncertain information and identify weights of criteria in the MCDM problem. By utilizing the beta distribution and approximating its median, we convert various types of expert evaluations including imprecise values into crisp values. We ensure consistency in each evaluation matrix before aggregating expert judgments. We then demonstrate use of the model by applying it to sustainable biomass crop selection. In order to define a comprehensive list of the selection criteria, we utilize the existing literature and opinions of experts including farmers, government specialists from the U.S. Department of Agriculture (USDA), and faculty members in the areas of biomass and bioenergy. The evaluation model includes three main sustainability criteria defined as economic, environmental, and social aspects associated with a total of 16 sub-criteria. We apply the proposed model to biomass alternatives including switchgrass, Miscanthus, sugarcane, corn, and wheat in Kansas. Results show the weights of economic, environmental, and social aspects to be 0.59, 0.26, and 0.15, respectively. The sensitivity analysis indicates that the score of switchgrass increases if environmental criteria are emphasized. On the other hand, wheat and corn become more favorable than other alternatives if priority is given to economic factors. The most sustainable biomass sources in different regions can be determined by applying the presented selection hierarchy. The proposed stochastic AHP methodology can also be utilized for other complex multi-criteria decision-making problems with uncertain information and multiple stakeholders.

1. Introduction

Finding the best source for sustainable energy production is of great importance since fossil-based energy is known to be limited and not environmentally friendly. Ethanol has the potential to replace fossil-based fuel and is practically used in many countries. However, due to the variability of biomass sources in different countries, selection of the most sustainable source for ethanol production becomes a significant question.

Sustainability is described as long-term development integrating three dimensions: continuous economic growth, environmental friendliness, and improved social welfare (Frini, 2014; Streimikiene, Balezentis, Krisciukaitiene, & Balezentis, 2012). In order to address the economic dimension of the sustainable biomass crop selection, we consider the financial implications of biomass crop type such as biofuel conversion rate, yield amount, and input cost for different farm operations. Furthermore, other economic factors such as technology, length of crop life, and equipment requirement also make the selection of biomass crop a strategic and operational decision. The environmental dimension of sustainable biomass crop selection requires the consideration of soil erosion, carbon dioxide sequestration, biodiversity, and pollution of water so that the biomass crop production will not harm the environment (Blanco-Canqui, 2010). Finally, in order to address the social dimension of the sustainable biomass crop selection, associated social impacts such as unemployment rate, working conditions, and welfare of the society should be included in the decision-making process (Kaffka, Jenner, Wickizer, & Williams, 2006; Sagisaka, 2008).

Because of these various economic, environmental, and social aspects, a multi-criteria decision analysis (MCDA) tool is needed for selecting the most sustainable biomass crop type. Multi-criteria decision-making (MCDM) techniques are utilized in real-life problems when there is a set of alternatives along with various criteria

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involved in the decision-making process. In many cases, the criteria have different units, such as dollars, time, dimensions, etc., which also make the acquisition of convenient data very expensive and the comparison among criteria difficult during the decision-making process. For this reason, researchers have proposed a number of methods for MCDM that perform differently and are capable of solving such complex problems (Peng, Wang, & Wang, 2012; Triantaphyllou & Mann, 1995). The analytic hierarchy process (AHP), which was developed by Saaty (1977), is a MCDM tool for dealing with complex decisions and is easy for decision-makers (DMs) to use in solving complex problems. In this paper, we propose a stochastic AHP approach for sustainable biomass crop selection since this method is particularly effective for cases where there are multiple options and uncertainty in the evaluation. The remainder of this paper is organized as follows: In Section 2, we review the literature regarding the methods for biomass crop type selection and define the problem statement. In Section 3, we propose the criteria to be considered in the sustainable biomass crop type selection, and explain potential and currently used crop type alternatives in Kansas. In Section 4, we present, step by step, the proposed stochastic analytical hierarchy process (SAHP). In Section 5, we demonstrate the application of the proposed model and present results along with a sensitivity analysis. Finally, we provide concluding remarks along with some discussion in Section 6.

2. Literature review

The nature of problem solving in MCDM methods involves a number of steps: defining the problem, eliciting relevant criteria, weighting the criteria and elements, defining alternatives, and ranking alternatives. In a similar manner, the AHP provides a rational and comprehensive framework for structuring a problem, comparing and weighting the criteria in the structure, and ranking the alternatives (Lazarevska, Fischer, Haarstrick, & MüNnich, 2009). The AHP has been widely applied in many problems, from the selection of energy alternatives to the selection of suppliers and academic personal (Deng, Hub, Deng, & Mahadevan, 2014; Kahraman & Kaya, 2010; Rouyendegh & Erkan, 2012). Although it has been criticized for some issues such as the rank-reversal problem (i.e., introduction of a new alternative may change the previous rankings), studies have been undertaken to make the AHP more robust, consistent, and efficient.

One approach for improving the AHP is to elicit expert opinions and convert them into numbers, since the scale used in the evaluation of criteria does not always have crisp values. Therefore, Van Laarhoven and Pedrycz (1983) introduce a fuzzy model where experts can compare two elements with a range rather than a crisp value. Various fuzzy AHP approaches and models were developed later by many researchers. Kahraman and Kaya (2010) utilize a fuzzy AHP for selecting the best energy alternative. Similarly, the fuzzy AHP method is utilized to select suppliers for the airline industry (Rezaei, Fahim, & Tavasszy, 2014). Another approach in supplier selection is developed by Kar (2014) who integrates a fuzzy AHP and fuzzy goal programming for group decision-making. However, as the authors state, the quality and quantity of data required to train their model may affect the separation of highly capable suppliers from less-capable ones. In addition, representing the linguistic scales by fixed triangular fuzzy numbers with a predefined range—such as (1, 3, 5) or (7, 8, 9), where numbers represent lower bound, most likely value, and upper bound, respectively—lacks the stochastic nature of expert opinion. In order to handle uncertainty in an expert judgment, Abdullah and Zulkifli (2015) multiply weights obtained from a fuzzy AHP with causal relations (correlation) between criteria in a human resources management problem. Although their method captures uncertainty in linguistics judgments, it is computationally costly and still does not capture the flexibility between upper and lower bounds in pair-wise comparison. Unlike these studies, in our model, an expert can flexibly define changing ranges when conducting a pair-wise comparison. Also, the most likely value is not always necessarily in the middle of this range, i.e., (1, 3, 5) can be defined as (1, 2, 5) in our model.

In order to handle the shortcomings of the fuzzy AHP, Jalao, Wu, and Shunk (2014) propose a stochastic AHP where they represent the varying preferences of the DMs by the beta distribution pair-wise comparisons. They propose a nonlinear optimization model that defines crisp values to ensure the highest consistency in the comparison matrix. However their nonlinear model can be computationally complex and can define crisp values that may not necessarily reflect the intention of the decision-maker. Another stochastic MCDM is proposed by Jato-Espino, Rodriguez-Hernandez, Andrés-Valeri, and Ballester-Muñoz (2014) to address uncertainty in the elements of hierarchy by utilizing Monte Carlo simulations. They consider a probability density function that provides the performance degree of each alternative while using a predefined margin of the upper and lower bounds for fuzzy evaluations. Furthermore, Durbach, Lahdelma, and Salminen (2014) let experts define their range for the evaluation. They aggregate these evaluations by defining the new range with minimum and maximum values of individual expert opinions. They utilize simulation to randomly draw a crisp value between the upper and lower bounds. However, as also stated by the authors, their method involves a risk of observing inconsistency after aggregation, even if each expert is consistent in the individual evaluation. In both studies, solution quality is highly dependent on the number of iterations and the probability distribution chosen for expert opinions. On the other hand, increasing the number of simulations results in reduced bias but also longer computational time. In contrast to the previous work on AHP methods, our model extracts the crisp value by approximating the median of the beta distribution. In cases where the consistency threshold is not satisfied, experts are asked to make a re-evaluation. That is not only a straightforward method when compared with a nonlinear optimization model or a simulation, but it is also a flexible approach where we can select mode or mean as a crisp value. In addition, unlike some of the aforementioned work, we also consider group decision-making after checking for consistency in each expert judgment.

In the literature, different methods have been proposed in the biomass field. For example, Kahr, Wimberger, Schürz, and Jäger (2013) evaluate the lignocellulosic ethanol potential of various agricultural residues by conducting real experiments. They test cellulosic biomass, such as wheat straw, rye straw, oat straw, and corn stover for second-generation ethanol. Santchurn, Ramdoyal, Badaloo, and Labuschagne (2014) evaluate four commercial varieties of sugar cane using a randomized complete block design. They identify variable proportions of sucrose and fiber in these biomass genotypes. Vaezi, Passandideh-Fard, and Charmchic (2012) develop a numerical algorithm for the selection of biomass alternatives for gasification purposes. However, they only focus on one particular aspect of biomass types. To the best of our knowledge, an AHP model has not been previously developed for sustainable biomass crop type selection.

Some studies utilize MCDM methods and the AHP in areas related to renewable energy and biomass. For example, Van Dael et al. (2012) propose an AHP model for selecting the location in a region for biomass valorization. They identify four main criteria and 22 sub-criteria, and apply the model in Belgium in order to determine potentially interesting locations to establish a biomass project. Balezentiene, Streimikiene, and Balezentis (2013) offer a