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A fuzzy approach to a multiple criteria and Geographical Information System for decision support on suitable locations for biogas plants

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HIGHLIGHTS

- We propose the GAF decision support methodology for optimal site selection.
- The GAF methodology builds decision support from multi-dimensional imprecise data.
- We present a real-case application for biogas facilities at Ringkøbing-Skjern, Denmark.

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ABSTRACT

The purpose of this paper is to model the multi-criteria decision problem of identifying the most suitable facility locations for biogas plants under an integrated decision support methodology. Here the Geographical Information System (GIS) is used for measuring the attributes of the alternatives according to a given set of criteria. Measurements are taken in interval form, expressing the natural imprecision of common data, and the Fuzzy Weighted Overlap Dominance (FWOD) procedure is applied for aggregating and exploiting this kind of data, obtaining suitability degrees for every alternative. The estimation of criteria weights, which is necessary for applying the FWOD procedure, is done by means of the Analytical Hierarchy Process (AHP), used jointly with the LLSM-AHP for the estimation of upper and lower bounds for the weights. Then, a combined AHP-FWOD methodology allows identifying the more suitable sites for building biogas plants. We show that the FWOD relevance-ranking procedure can also be successfully applied over the outcomes of different decision makers, in case a unique social solution is required to exist.

The proposed methodology can be used under an integrated decision support frame for identifying the most suitable locations for biogas facilities, taking into account the most relevant criteria for the social, economic and political dimensions.

1. Introduction

Decision making on the location of new facilities is a problem that requires considering multiple different criteria jointly with geographical information for arriving at a satisfactory solution [1–4]. Under a decision support system's approach, the selection of facility locations needs an automatic and interactive methodology capable of dealing with large amounts of data, understanding and solving the problem in a descriptively satisfactory way. Such a methodology must take into account the different types of uncertainties involved in common measurements, like e.g., lack of specificity [5], hesitation [6] or vagueness [7–9], and the need to arrive at a solution where general consensus exists.

In order to build the necessary and sufficient knowledge for understanding and solving the facility location problem, decision support has to work under natural conditions of uncertainty. Here we refer to *imprecision* in order to deal with the uncertain *quality* of information [10,11]. Under this perspective, imprecision is a primary attribute of common measurements, taking the form of a unique value if it is precise, or of an interval set of values if it is imprecise.

For example, the measurement of the production potential for a given biogas facility site is largely determined by the slurry production at the nearby farms. Therefore, the *proximity* of the site to the biomass sources has to be taken into account, modeling *proximity* as a function of the distance from the site to the respective farms that are within a local service area. The service area

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refers to imprecise information, in the sense that different farms are in fact near the site and there is not a unique farm serving as single source for each site. Then, the set of farms being considered as sources of biomass can be characterized by the minimal and maximal driving distances to a specific site, implying an imprecise estimation for the degree of production potential given by a lower and an upper bound.

In this paper a new methodology is introduced for treating imprecise geographical measurements and multiple criteria under a common analytic framework (following the initial approach presented in [10]). Such measurements are gathered by means the Geographical Information System (GIS), and the aggregation and exploitation of the available information is done using the Fuzzy Weighted Overlap Dominance (FWOD) model [11,12]. This multiple criteria model requires the previous specification of user-defined threshold parameters, for determining the relational situation between overlapping intervals, as well as an estimation of the criteria weights expressing their relative importance. The estimation of such weights is done following the elicitation of expert's opinions and evaluating them according to the Analytical Hierarchy Process (AHP) (see e.g. [13,14], but also [15]). As a result, the decision maker is able to read a certain ranking over all the alternatives, determining when an alternative is either preferred to or indifferent with another one.

The integrated GIS-AHP-FWOD (GAF) methodology proposed here is applied over possible locations for slurry based biogas plants in the municipality of Ringkøbing-Skjern, Denmark, where biogas based energy production plays an important role in accomplishing local ambitions for a self-sufficient renewable energy consumption by 2020. The ambition is that 80% of the local slurry resources are converted to biogas [16], using animal manure as the main feedstock for producing combined renewable heat and electricity.

The primary objectives of this paper are:

(i) Offer an integrated decision support framework for handling geographical information, imprecise measurements and opinions from experts on the relative importance of criteria, obtaining a ranking over the alternatives based on their overall relevance.
(ii) Define a reliable methodology for supporting the problem of choosing suitable biogas plant locations considering population density, production potential, municipality planning and distances to heat plants and transportation-optimal sites.

Different proposals for bioenergy location studies, applying multiple criteria decision making (MCDM) methodologies can be found in literature (see e.g. [3,17–20]), representing around 6% of all bioenergy MCDM studies [21]. In general, such proposals make use of GIS and consider location-allocation analysis where road network data is taken into account (avoiding over simplified Euclidean distances between points). Consequently important information is included for examining the complexities of real world problem situations. In particular, referring to the criteria being normally considered, resource availability and transport optimization are the ones that receive more attention (see e.g. [3,18,20]).

It has also been suggested that in an urban energy planning context the demand side issues should dominate the location decision [22], considering e.g. environmental aspects [23]. The opposite position argues that when dealing with bioenergy facility location, the supply side should dominate [24], which is further supported by the notion of the *logistical trap* [25], since the energy density is much lower in bioenergy sources than in fossil fuel. Besides, infrastructural considerations should also be taken into account [26], together with biomass production costs for power production [27] and biomass potentials [28].

Special consideration deserves the proposal for recommending the best locations for biogas plants in southern Finland [3], where the authors present a solid methodology based on the potential biomasss feedstock for biomethane production. This approach points out two main drawbacks in their MCDM bioenergy location study, namely the fine scale in which data has to be usually treated and the exclusion of political/environmental and social criteria. The former has negative implications on the feasibility of the methodology over specific areas where such fine data is not be available, while the latter refers to the necessity of a general framework flexible enough to examine potential political, environmental and social constraints.

The present paper contributes to the emerging bioenergy location MCDM literature, by means of a decision support system that allows handling imprecise information on the multiple criteria regarding not only economic, but also political, social and environmental aspects. This is done by taking the geographical measurements and eliciting expert opinions on the relative importance of criteria, and aggregating the available data under a fuzzy decision support framework, extracting relevant knowledge and ranking the alternatives from best to worst. As a result, the decision maker (DM) can understand the large amounts of information regarding the candidate sites, arriving at satisfactory solutions based on economic grounds and at the same time, fulfilling political and social restrictions.

This paper is organized as follows. Section 2 introduces the case study and the set of criteria that is used to evaluate the suitability of the candidate sites. In Section 3, the theoretical framework for extracting knowledge from imprecise measurements is developed, in order to obtain the ranking of alternatives. Section 4 presents the results of the GAF decision process for biogas plant location, comparing them with a more traditional approach making use of *precise* data, and Section 5 discusses the results for different layouts of the biogas network. Finally we end with some conclusions and future lines of work.

2. Materials and methods

This research focuses on building decision support for choosing the location of biogas plants according to a given set of criteria. The geographical information is gathered using the ArcGIS 10.1 software [29].

2.1. Case study

From 2013, all Danish municipalities have been obliged to develop biogas plans as an integral part of their energy policies. As part of the efforts of implementing EU regulations, Denmark has set forth an ambitious strategy concerning bioenergy from the agricultural sector, especially for biogas. Municipal planners play an important role in deciding on suitable areas for biogas production. Hence, the methodology introduced in this paper is aimed at providing support for decision makers (DMs), i.e., planning authorities, focusing in the case of the municipality of Ringkøbing-Skjern. This municipality is the largest and one of the least populated areas in Denmark, with a population of 57.330 inhabitants among its 1470 km^2 [30].

The fact that Ringkøbing-Skjern has an approximated stock of 566.000 animal units of pigs and 484.000 animal units of dairy cattle within its boundaries [30], combined with the policy ambitions in Ringkøbing-Skjern, provide a good basis for a case study on how the GAF methodology can provide decision support to a real bioenergy-based facility location problem.