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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), such that 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.

Keywords: Decision support, Multiple criteria, Geographical information, Interval data, Facility location, Biogas plants

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 [7, 13, 14, 16]. Under a decision support

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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 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*, a particular type of uncertainty referring to the quality of the information [8, 9], not to be associated to uncertainty due to the presence or lack of information (see e.g., [4, 20]). Under this perspective, imprecision is a primary attribute of any kind of measurement which takes the form of a unique value if it is precise, or of an interval set of values if it is imprecise.

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 [8]). 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 [9, 15]. 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. [24, 25], but also [30]). 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 [2], 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. [14, 22, 23, 27, 28]), representing around 6% of all bioenergy MCDM studies [26]. 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 optimisation are the ones that receive more attention (see e.g. [14, 23, 28]). Special consideration deserves the proposal for recommending the best locations for biogas plants in southern Finland [14], 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 may not be available, while the latter refers to the necessity of a general framework flexible enough to examine potential political/environmental and social constraints.

These are the two issues that the present paper attempts to address, contributing to the emergent bioenergy location MCDM literature field, by means of a decision support system that allows handling imprecise information on the multiple criteria regarding economic, political and social aspects. This is done by taking 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 better to worse. As a result, the decision maker (DM) can understand the large amounts of information regarding the candidate sites, arriving to satisfactory solutions based on economical grounds and at the same time, fulfilling political and social restrictions.

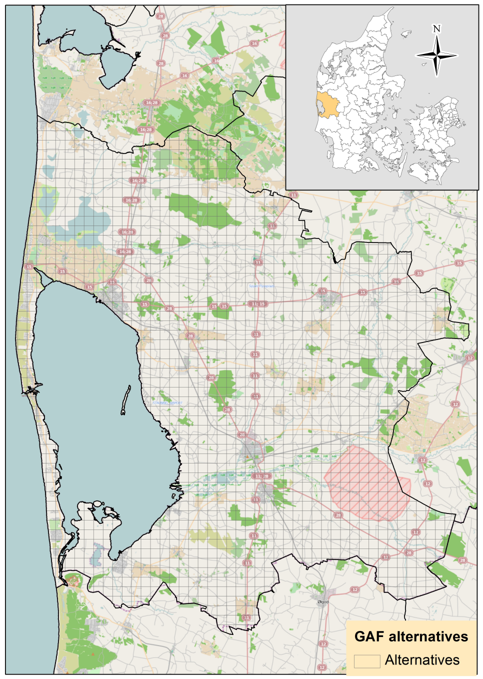
2. Materials and methods

This research focuses on buiding 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 [6].

2.1. Case study

From 2013, all Danish municipalities have been obliged to develop biogas plans as an integral part of their energy policies. 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 [5].

Figure 1: Sites of 1 km^2 for building biogas plants in the municipality of Ringkøbing-Skjern



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 [5], 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.

2.2. Candidate biogas plant locations

With the objective of identifying the candidate sites for biogas plants, the whole territory of Ringkøbing-Skjern is arbitrarily divided into cells of 1 km^2, i.e., 100 ha (as shown in Fig. 1). The selection of this 1 km^2 scale corresponds to the specific charcaterisitcs of this case study and could be adjusted if necessary without affecting the general methodology. In this way, previous to any calculation, all of the municipality's territory is considered a suitable location area. Interval measurements are obtained for every alternative geocell regarding the set of given criteria.

Notice that the site size should leave enough room for the DM to engage in subsequent analysis over more specific parameters, such as the precise design or the capacity of the biogas plant. For example, in the particular case of Denmark, the average area for existing biogas plants is 4 ha. Since future biogas plants are expected to require a somewhat larger area, the specification of the 1 km^2 candidate sites is intended to include a sufficiently large margin (each one of them can accommodate multiple average biogas plants) for the DM to evaluate with more technically case-dependent information the precise location of the plant.

2.3. Determination of relevant criteria

The multiple criteria involved in the site selection decision problem refer to the most relevant factors that policy authorities and municipal planners have to consider in order to understand and solve the problem in a satisfactory way. Hence, the determination of the set of criteria has a direct impact on the quality and relevance of the results.

The selection of the decision criteria for this case study is based on [7], where a review of the most important criteria used to solve facility location problems is found. Such general criteria are given by:

(a) Political matters
(b) Cost evaluations
(c) Economic issues
(d) Value and benefit considerations
(e) Resource availability
(f) Population acceptability
(g) Production capacity
(h) Competitiveness

In this way, in order to achieve the sustainable facility location objectives, five criteria are formulated covering environmental, economic, social and political concerns, as shown in Table 1. These criteria are defined in collaboration with the Danish biogas secretariat (part of the Danish nature agency):

(A) Planning zone suitability
(B) Distance to transport economic optimal sites
(C) Production potential
(D) Population density
(E) Distance to heating plants

Criteria A-E cover the most important aspects involved in the facility location problem [7], providing a solid basis for decision support for the municipality of Ringkøbing-Skjern. (A) Planning zone suitability covers the political matters of the plant location, which to a large extent is concerned with environmental issues; (B) distance to transport economic optimal zones refers to the evaluation of costs and benefits, where it is known that an important part of the production costs in biogas production in Denmark is positively associated to the transportation of slurry from farms to biogas plants; (C) production potential includes resource availability and general capacity issues; (D) population density examines social acceptability in the sense that lower density levels indicate higher population acceptability; and (E) distance to heating plants covers competitiveness and availability aspects between biogas and heating plants. Data for valuing the alternatives according to the selected criteria come from an open source database managed by the Danish nature agency [19], containing spatial planning information from all Danish municipalities.

Table 1: General criteria, case study criteria and their respective objectives

General criteria	Case study criteria	Objectives
(a)	Degree of planning zone suitability	Maximize
(b), (c), (d)	Distance to transport economic optimal zones	Minimize
(e), (g)	Production potential	Maximize
(f)	Population density	Minimize
(h)	Distance to heating plants	Minimize

2.4. Valuation of alternatives

2.4.1. Degree of planning zone suitability

The information for building the planning zones suitability degrees has been developed by the Danish nature agency [19] in cooperation with Danish municipalities. The available knowledge on the suitability of the alternatives is given by four classes of regions depending if they are strongly favourable, semi-favourable, semi-disfavourable or strongly disfavourable areas when considering a number of environmental reasons and planning legislative restrictions. In this way, there exists an interval planning zone suitability degree for every alternative, which is measured by means of the favourable and not disfavourable information (an initial study on FWOD decision support based on acceptability and rejectability degrees can be found in [8]).

2.4.2. Distance to transport economic optimal zones

As transportation of slurry accounts for 30-50% of the overall biogas production costs [3], the minimization of this factor is regarded as a crucial cost criterion for identifying suitable locations. In this study, the transport economic optimal zones are evaluated through locate-allocate analysis carried out in ArcGIS [6], by which the supply weighted transport distance between all plants and farms is minimized. Once such transport economic optimal zones are identified, Euclidean distances are measured between them and all the biogas candidate sites, by means of a distance raster with cell size of 100 m. By performing a spatial join in ArcGIS 10.1 between each alternative grid cell and the distance raster, and taking the minimum and the maximum values within each alternative, the lower and upper bounds for the distance measurements are obtained.

2.4.3. Production potential

The production potential for each alternative within Ringkøbing-Skjern municipality is based on the sum of slurry production at farms larger than 30 animal units within an area of 30 and 40 km driving radius, defining the respective lower and upper bounds of the measurements. These areas are calculated through a network analysis, carried out in ArcGIS [6], for every alternative's centroid.

2.4.4. Population density

Regarding population acceptablity, the fewer people living in the vicinity of a biogas plant, the fewer will be exposed to the potential annoyances of the plant, such as increased transports, noise and the perceived risk of smell. Data for the population densities are obtained from Statistics Denmark [5], based on the Danish central person register from January 1, 2012.

These data are obtained at a 100 m^2 scale and have to be subsequently aggregated in order to express the proper measurements for the 1 km^2 alternatives. Notice that the GAF methodology is a robust procedure for dealing with biases that may rise from aggregation procedures over spatial point-based measures, as in the modifiable area unit problem [21], by including imprecise measurements over the 1 km^2 grid cells and by shifting the cells in order to include broader boundaries. This is done by shifting each geocell 200 m NW, SW, NE and SE. For each one of these shifted locations, population density is calculated, and lower and upper bounds result from the minimum and maximum values associated to each alternative and its vicinity.

2.4.5. Distance to heat plants

The distance to heat producing plants includes combined heat and power plants (CHP) as well as heat plants. Distances are calculated based on Euclidian minimum and maximum distances from every alternative to the location of CHP and heat plants [19]. This data offers relevant information since the expansion of district heat networks are very costly, whereas biogas pipelines from the actual biogas plant to the heat plant are relatively cheap in comparison (app. 10 times less expensive than heat pipes).

2.5. Modelling the decision making process

Based on a (AHP designed [25]) pairwise comparison survey among Danish central governmental biogas officers, the relative importance for the biogas location criteria is examined. Characterizing these officers as plausible DMs, five different scenarios are represented according to the specific selection of the system's free parameters (which will be explained in detail in the following Section). In this way the existence of different DMs can be explored under the general framework of the GAF methodology, examining the sensitivity of the alternatives ranking with respect to the heterogeneity of DMs.

Scenario 0 represents a base scenario representing a neutral modeling approach (in fact, it is the scenario that the system adopts by default). Scenario

1 and 2 represent cases where the DM has different attitudes towards the dominance or outranking threshold between alternatives, where a very small difference between their scores can be enough to affirm that one alternative dominates another one (scenario 1), or on the contrary, a higher difference is required by the DM to affirm such dominance (scenario 2). On the other hand, scenarios 3 and 4 respectively represent risk affine and risk averse DMs.

3. Theory

The WOD outranking procedure has been initially presented in [15] for treating multidimensional interval data under a decision support system's approach. In this Section, a fuzzy model for the WOD procedure is further developed (following [9]), examining the way in which interval data can be analytically represented for arriving to a relevance ranking of the alternatives. Besides, the AHP is used for estimating criteria weights, which are needed along with the alternatives' values with respect to the given criteria as input data for the FWOD model. In this way, the foundation of the GAF methodology can be established for supporting biogas plants location problems.

3.1. Fuzzy aggregation of imprecise information

Fuzzy set theory offers a mathematical analytic framework for examining common evaluations over a given set of objects of interest [11, 31]. Here, such objects are given by the set of alternatives N with cardinality $|N| = n$, which are valued according to the set of criteria M, $|M| = m$, obtaining a fuzzy degree according to the intensity in which the alternatives verify each criterion. In order to take account of the natural imprecision found in common measurements, and to maintain and use such imprecision along the inference process, fuzzy degrees can be expressed in interval form [1, 4, 12].

In this way, for any $a \in N$, the fuzzy degree

$$\mu_i(a) = \left[\mu_i^L(a), \mu_i^U(a)\right] \in [0,1]^2 \tag{1}$$

represents the extent up to which alternative a verifies some criterion $i \in M$, such that $\mu_i^L(a)$ is the lower bound and $\mu_i^U(a)$ is the upper bound of $\mu_i(a)$. Then, for every $a \in N$, all of the associated criteria evaluations (1) are aggregated into an m-dimensional cube

$$c_a = \left[\mu_i^L(a), \mu_i^U(a)\right]^m, \tag{2}$$

which represents the input data for the FWOD model.

Here it is noticed that if the objective is to minimize criterion i, the degree μ_i has to be accordingly transformed by some involutive operator $\neg$, in order to be handled appropriately by the FWOD procedure, which ranks alternatives according to their highest scores. For example, taking i =*population density*, input data have to represent its dual-opposite property, which can be understood as *population dispersion*, referring to the social acceptability for building a biogas plant in some location $a \in N$. In this way, if the degree μ_i associated to the criterion i has to be minimized (see Table 1), it can be transformed by means of some negation operator $\neg$, such that $\neg(\mu_i) = \left[\neg(\mu_i^U), \neg(\mu_i^L)\right]$.

Once the input data set is given as in (2), its magnitude or volume agrees with its overall imprecision [9], which is measured by the imprecision-volume operator V. This enables the FWOD procedure to build an outranking order over N, maintaining and exploiting the imprecision of the information along its inference process. Such procedure (initially presented in [15]) is based on a given vector of criteria weights $w \in \mathbb{R}_m^+$, and the definition of the following sets for every $a, b \in N$,

$$\hat{Z}(a,b) = \left\{x \subseteq c_a | w \cdot x^L \geq w \cdot \mu^U(b)\right\}, \tag{3}$$

$$\check{Z}(a,b) = \left\{x \subseteq c_a | w \cdot x^U \leq w \cdot \mu^L(b)\right\}, \tag{4}$$

$$\tilde{Z}(a,b) = \left\{x \subseteq c_b | w \cdot x^L \geq w \cdot \mu^L(a)\right\}, \tag{5}$$

where $\mu^L(a) = \left(\mu_1^L(a), ..., \mu_m^L(a)\right)$ and $\mu^U(a) = \left(\mu_1^U(a), ..., \mu_m^U(a)\right)$; x is some m-dimensional cube $x = \left[x^L, x^U\right]$ defined for each set (3)-(5) such that $x^L = \left(x_1^L, ..., x_m^L\right)$ and $x^U = \left(x_1^U, ..., x_m^U\right)$; and alternatives $a, b \in N$ are such that $w \cdot \mu^U(a) > w \cdot \mu^U(b)$ (for more details see [9, 15]).

Now, the DM may interact with the model by means of three parameters α, β and γ, according to the following considerations.

Firstly, the parameter $\alpha \in [0,1]$ allows reducing the number of alternatives being considered in the analysis, focusing on the ones that obtain a higher position in the outranking order. By default, all the alternatives are included, such that $\alpha = 0$. This value can be changed such that the closer it is to 1, the less number of alternatives are considered.

Secondly, the outranking situation for any pair of alternatives is determined by specific thresholds given by $\beta \in [0,1]$ and $\gamma \in \mathbb{R}^+$. In the case there exists partial overlap between c_a and c_b, such that $\check{Z} = \emptyset$ holds, then *a outranks b*, i.e., $a \succ b$, only if it holds that

$$\frac{V(\hat{Z})}{V(c_a)} + \frac{V(c_a \setminus \hat{Z})}{V(c_a)} \frac{V(c_b \setminus \tilde{Z})}{V(c_b)} > \beta. \tag{6}$$

Notice that inequality (6) only considers sets (3) and (5), where the first term of the sum refers to the proportion or likelihood that c_a completely exceeds c_b, while the second term computes the conditional likelihood of c_a outranks c_b given that c_b is at least as good as c_a. Hence, the complete expression refers to the available data justifying the outranking of a over b, and the DM is able to specify the threshold β for determining such outranking. Otherwise, both alternatives are considered *indifferent*, where $a \sim b$ holds.

By default, β is taken such that $\beta = 0.1$, such that a small difference between the upper or lower bounds of c_a and c_b is enough for obtaining an outranking relation. If the DM has a greater tolerance for such differences, β can be adjusted by taking higher values.

On the other hand, in the case that there exists complete overlap between c_a and c_b, such that $\check{Z} \neq \emptyset$ holds, then the relational situation between a and b depends on the ratio that exists between the imprecision magnitude of (3) and (4), given by

$$V(\hat{Z})/V(\check{Z}). \tag{7}$$

Hence, if (7) is greater, equal or less than γ, it respectively holds either that $a \succ b$, $a \sim b$ or $b \succ a$.

By default, γ is taken as being equal to 1 (risk-neutral), such that any pair of alternatives $a, b \in N$ are taken to be indifferent only if the amount of c_a completely exceeding c_b is equal to the amount of c_a that is completely exceeded by c_b. In any other case, an outranking situation holds, and the DM is able to revise the value of γ with a higher (risk-averse) or lower (risk affine) value if the threshold for establishing the outranking of a over b is respectively more or less demanding (for more details see [15]).

Notice that there is a certain difficulty when determining a unique value as a threshold for obtaining either an indifference or an outranking situation: if the DM assigns a more demanding threshold for obtaining an outranking situation of a over b, then automatically a less demanding threshold is assigned so that b outranks a. Hence, such threshold could refer to an interval of values or a linguistic label expressing in a more general and flexible way the attitude of the DM. For example, defining $\gamma^{IV} \in [0,1]^2$, such that indifference exists every time that (7) lies inside the region given by $\gamma^{IV} = [\gamma^L, \gamma^U]$, where $\gamma^L \leq \gamma^U$. Then, a outranks b only if (7) is greater than γ^U and b outranks a only if (7) is less than γ^L. This extension can be further studied in future work, taking into account the fuzzy-linguistic approach of [10, 18, 29].

Following the DM's specification of the three parameters α, β and γ, it is necessary to address the estimation of the vector of weights w, which allow comparing criteria in a direct way. This is important for establishing the trade-off between criteria and their complete comparability, which lays the foundation for the FWOD outranking approach. Next, we explain the estimation process for w based on the AHP evaluation of experts' opinions.

3.2. Estimation of criteria weights

Up to now we have been assuming the existence of a vector of weights w, representing the importance of the criteria. These weights are essential to the overall aggregation of the criteria, establishing a hierarchy between the different factors that come into play for arriving to an informed judgment over the decision problem (see e.g. [24, 25]). Here, the AHP is used for consistently estimating the vector of weights, based on expert knowledge regarding the relative importance of the criteria in M.

The AHP is a weight estimation technique that has been extensively used in multiple criteria decision making literature [7, 16, 25, 28], where the objective is to understand and aggregate different expert judgments. Such judgments are elicited by means of linguistic pairwise comparisons between the objects of interest (in this case criteria), building up a reciprocal matrix from where the analysis develops (see [24]). This standard AHP makes use of a valuation scale where one linguistic label corresponds to a crisp value or precise number, but it is noted that an extended fuzzy logarithmic least squares AHP (LLSM-AHP) can be also applied for examining fuzzy judgments, where fuzzy numbers are used instead of crisp values, as done in [17, 30].

Here, given the interval form of data $\mu_i = \left[\mu_i^L, \mu_i^U\right]$, the LLSM-AHP can be used under a modified version for obtaining interval weights $w^{IV} = \left[w^L, w^U\right]$, where $w^L = \left(w_1^L, ..., w_m^L\right)$ and $w^U = \left(w_1^U, ..., w_m^U\right)$, such that (3)-(5) are respectively transformed into,

$$\hat{Z}^{IV}(a,b) = \left\{x \subseteq c_a | w^U \cdot x^L \geq w^U \cdot \mu^U(b)\right\}, \tag{8}$$

$$\check{Z}^{IV}(a,b) = \left\{x \subseteq c_a | w^L \cdot x^U \leq w^L \cdot \mu^L(b)\right\}, \tag{9}$$

$$\tilde{Z}^{IV}(a,b) = \left\{x \subseteq c_b | w^L \cdot x^L \geq w^L \cdot \mu^L(a)\right\}. \tag{10}$$

In this way, the fuzzy LLSM-AHP [30] is modified in order to obtain a fuzzy interval weight vector w^{IV}, formulating the following constrained optimization problem for a given set of experts E, such that $q \in E$, $q = 1, ..., e$,

$$\begin{aligned} \text{Min } J \;=\; & \sum_{i=1}^{m} \sum_{j=1, j\neq i}^{m} \sum_{q=1}^{e} (\ln\, w_i^L \,-\, \ln\, w_j^U \,-\, \ln\, \nu_{ijq}^L)^2 \\ & \qquad\qquad + (\ln\, w_i^U - \ln\, w_j^L - \ln\, \nu_{ijq}^U)^2 \\ \text{s.t.} & \begin{cases} w_i^L + \sum_{j=1, j\neq i}^{n} w_j^U \geq 1, \\ w_i^U + \sum_{j=1, j\neq i}^{n} w_j^L \leq 1, \\ \sum_{i=1}^{n} (w_i^L + w_i^U) = 2, \\ w_i^U \geq w_i^L > 0 \end{cases} \qquad i{=}1{,}...{,}m \end{aligned} \tag{11}$$

where $\nu_{ijq} = \left[\nu_{ijq}^L, \nu_{ijq}^U\right]$ makes reference to the respective lower and upper bounds of the expert q's evaluation of criterion i when compared with criterion j, such that $\nu_{ijq}^{-1} = [1/\nu_{jiq}^U, 1/\nu_{jiq}^L]$ and for $i = j$, $\nu_{ijq} = [1, 1]$.

As a result, solving (11) obtains w^{IV} for the direct application of (8)-(10), extending the procedure to include fuzzy interval weights (which can be further studied in future work). Next, the ranking of alternatives is explored, with the purpose of aggregating different DMs into an overall social outcome.

3.3. Ranking of alternatives

The FWOD procedure uses relevance measures σ, to rank the alternatives in N, based on the outranking order obtained by means of (3)-(5) and (6)-(7) (for the complete details see [9]). Relevance measures are defined over a totally ordered scale, where every alternative $a \in N$ is graded according to the number of alternatives that it outranks/dominates and the importance of such dominated alternatives.

Definition 1. Given the outranking relation $\succ$, and for every $a, b, c, d \in N$, let D_a represent the set of all alternatives that are outranked by a. Then, the function σ is a relevance measure, where σ_a represents the relevance degree of a, if and only if it fulfills the following axioms:

1. $\sigma_a = 0$ if and only if $D_a = \emptyset$.
2. If $a \succ b$ and $D_b = \emptyset$, then $\sigma_a > \sigma_b$.
3. If $D_a = \{N \setminus \{a\}\}$, then for every $b \neq a \in N$, $\sigma_a > \sigma_b$.
4. If $a \succ b$, $c \succ d$ and $b \succ d$, then $\sigma_a > \sigma_c$.

Definition 1 characterize relevance measures by means of axioms 1-4. The general intuition is that an alternative gains relevance with the number and the importance of the alternatives that it outranks. As a result, a ranking based on relevance measures is obtained, where each alternative is placed either higher than, equal to or lower than any other alternative.

Notice that given a set K, $|K| = k$, of different but equally important DMs, each of them assigning different values to α, β and γ, distinct outcomes can be obtained regarding the ranking of the alternatives. Therefore, an aggregation methodology is proposed for arriving to an overall ranking which maximizes the observed relevance of the alternatives.

In this way, for every $r \in K$, and for any $a \in N$, there exist a normalized relevance value given by σ_a^r, which can be aggregated over all the elements of K by means of

$$\sigma_a^K = \sum_{r=1}^{k} \sigma_a^r, \tag{12}$$

where it follows directly that σ_a^K is a relevance measure in the sense of Definition 1. As a result, an aggregated ranking over N can be obtained according to the relevance of every $a \in N$, given by (12). Therefore, all the rankings expressed by each DM can be aggregated into a comprehensive and egalitarian result, where every DM has the same importance, and alternatives are totally ordered according to their overall relevance.

Now the GAF methodology has been examined and extended for considering different DM rankings, laying the foundations for future work on fuzzy criteria weights and outranking threshold parameters. In the next Section, the results on its application over Ringkøbing-Skjern's data are presented and discussed.

4. Results

Following the GAF methodology, the set of alternatives are ranked in order to obtain the more suitable locations for building biogas plants in Ringkøbing-Skjern. Here the results are discussed, examining the aggregation of the five different scenarios and the feasibility of this methodology for solving general biogas plants location problems.

Table 2: The different scenarios according to the DMs specification of the parameters α, β and γ.

Parameters	Scenario 0	Scenario 1	Scenario 2	Scenario 3	Scenario 4
α	0.01	0.01	0.01	0.01	0.01
β	0.01	0.001	0.3	0.01	0.01
γ	1	1	1	0.7	1.3

4.1. The GAF decision process

Under the five DM scenarios, the parameters α, β and γ are defined as shown in Table 2. With α equal to 0, all of the candidate locations are included in the analysis, i.e., all of the geocells in Ringkøbing-Skjern municipality are taken into account. Regarding scenarios 1 and 2, the parameter β respectively takes lower and higher values. The smaller (higher) the value of β is, the more (less) likely that an outranking situation holds between the alternatives. On the other hand, scenarios 3 and 4 represent changes over the risk parameter γ, where neutrality is given by $\gamma = 1$, risk aversion is given by $\gamma > 1$ and risk affinity is given by $\gamma < 1$.

4.2. Biogas plant locations

The input data that each DM introduces into the system consists of (1) the m-dimensional cubes c_a for every alternative $a \in N$, (2) the vector of weights w according to the importance of each criterion $i \in M$ and (3) the values for the free parameters α, β and γ. As mentioned in Section 3, every DM may interact with the system by means of those free parameters. Then, the different rankings proposed by the group of DMs are aggregated into one overall ranking, assigning a total order over all of the 1 km^2 candidate sites for building biogas plants.

The results from the AHP estimation of the vector w can be seen in Table 3, where its respective lower and upper bounds, obtained by means of (11), are also presented. The consistency ratio associated to w is 0.049, where a ratio below 0.10 is considered acceptable ([24]). These results show higher weights for the criteria regarding the distance to transport economic optimal zones and slurry production potential, followed by the degree of planning zone suitability, population density and the distance to heating plants.

Given the interval estimation of w^{IV}, its respective bounds offer a general estimation for further analysis. Meanwhile no overlap exists between the two most important criteria, notice that the degree of planning zone suitability presents some overlap with the population density criterion. In such case, the lower bound of the former is less than the upper bound for the latter. Hence, there exists some space for considering interactions between them and the possibility of taking them as being similarily important.

Table 3: AHP estimation of the vector w of criteria weights and the LLSM-AHP estimation of its associated lower and upper bounds w^L and w^U.

Criteria	w^L	w	w^U
Degree of planning zone suitability	0.111	0.166	0.216
Distance to transport economic optimal zones	0.286	0.389	0.499
Production potential	0.223	0.253	0.264
Population density	0.095	0.113	0.136
Distance to heating plants	0.069	0.076	0.099

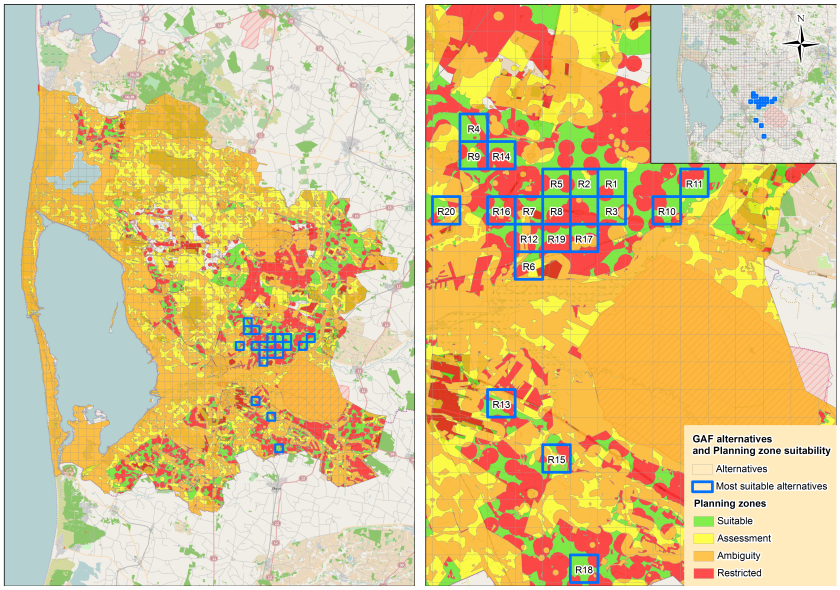
The results on the candidate sites ranking can be seen in Table 4 for the top 20 locations, where the relevance measures are given along the respective suitability and rejectability planning zone degrees. See also Fig. 2a where the same locations are pointed out in blue over the geographical map containing the municipality's planning zones, where green and yellow areas respectively refer to suitable and possibly suitable zones, while red and orange areas respectively refer to rejectable and possibly rejectable zones. Focusing on the planning interval degrees in Table 4, it can be seen that planning rejectability is not necessarily the complement of suitability, where the respective negative information of one planning degree does not imply the positive information of the other. Hence, both degrees offer distinct and important information on the municipality's planning situation towards building biogas plants. See e.g. in Table 4 that site R6 has low degrees for both, revealing some *hesitancy* over the planning situation of the alternative, or sites R15 and R16, where similar suitability degrees have associated dissimilar rejectability scores.

Following these results for decision support, the highly ranked alternatives deserve further examination, where biogas plants (which have a smaller extension than the 1 km^2 of the considered sites) should lie inside the identified locations but avoiding the rejected munipality planning zones. A close up on the selected alternatives (see Fig. 2b) shows the simultaneous appearance of acceptability-rejectability in every site, where it is a matter of selecting the green area inside each cell for building the biogas facility. Then, it is possible to maximize production potentials and minimize distances to optimality while respecting municipality planning schemes.

Focusing on the most important criteria, Fig. 3 shows the best sites and their

Table 4: The total relevance ranking for the best 20 sites along with their associated suitability and rejectability planning degrees.

Ranking	Site ID	Relevance	Planning suitability	Planning rejectability
1	R1	3.99	[0.78, 0.79]	[0.21, 0.21]
2	R2	3.54	[0.77, 0.80]	[0.15, 0.16]
3	R3	3.47	[0.69 0.69]	[0.22, 0.26]
4	R4	3.03	[0.70, 0.71]	[0.28, 0.28]
5	R5	3.01	[0.58, 0.58]	[0.42, 0.42]
6	R6	2.59	[0.20, 0.33]	[0.29, 0.41]
7	R7	2.15	[0.42, 0.44]	[0.40, 0.48]
8	R8	2.11	[0.43, 0.43]	[0.57, 0.57]
9	R9	1.84	[0.52, 0.54]	[0.43, 0.44]
10	R10	1.67	[0.52, 0.53]	[0.42, 0.45]
11	R11	1.53	[0.56, 0.57]	[0.43, 0.43]
12	R12	1.51	[0.26, 0.31]	[0.40, 0.53]
13	R13	1.46	[0.35, 0.36]	[0.34, 0.48]
14	R14	1.39	[0.44, 0.44]	[0.56, 0.56]
15	R15	1.21	[0.31, 0.39]	[0.31, 0.41]
16	R16	1.19	[0.34, 0.34]	[0.63, 0.64]
17	R17	1.00	[0.35, 0.35]	[0.30, 0.47]
18	R18	0.93	[0.66, 0.66]	[0.25, 0.29]
19	R19	0.89	[0.30, 0.31]	[0.69, 0.69]
20	R20	0.87	[0.32, 0.38]	[0.23, 0.40]



(a) (b)

Figure 2: Representation of the 20 highest scoring sites and the underlying planning suitability-rejectability zones

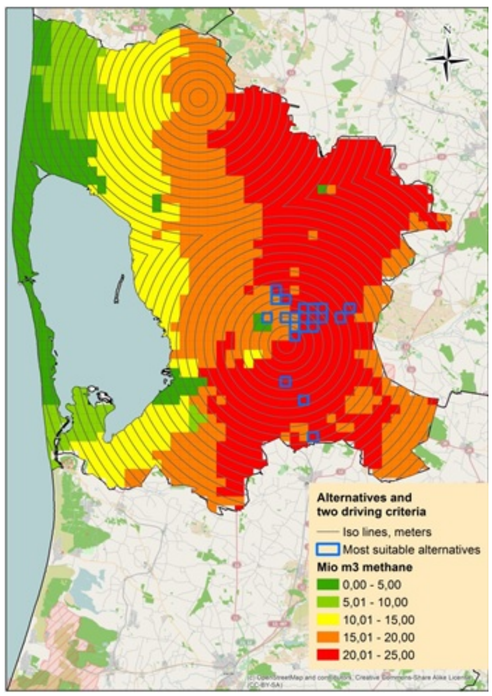
relation to transport economic optimal zones and slurry production potential, where the concentric lines represent the distance to the pair of optimal zones and the green to red colored areas represent the different levels of slurry production potential. In this way, each area respectively agrees with a potential production of [0,5], (5,10], (10,15], (15,20], up to the red area with a potential of (20,25] million m^3 of methane. It can be seen that these criteria have a high impact on the final results for the selected alternatives (as it could be expected from their estimated values in Table 3), where a strong clustering tendency exists around the economic optimal zone with greater production potential (17 of the 20 most preferred alternatives are located within an area of 60 km^2).

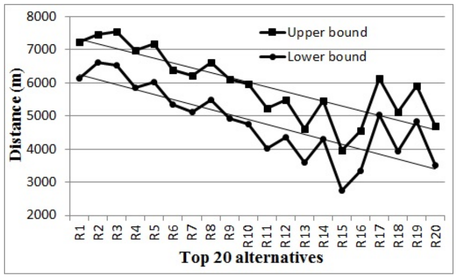
Therefore the GAF methodology offers robsut decision support recommending where to build new biogas facilities, justifying its results on the available information and the relative importance of the multiple criteria. Hence, it is a solid analytical tool that allows understanding a given set of data for extracting knowledge, where the most important viewpoints can be jointly taken into consideration, including not only economic optimals but also political/environmental restrictions and social reasons.

4.3. Variation of number of biogas plants

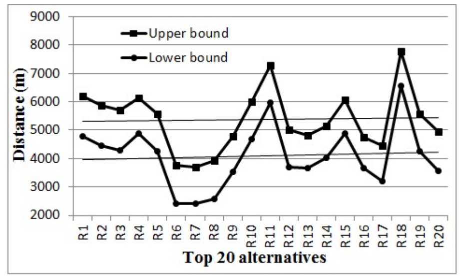
The results obtained from the implementation of the GAF methodology over Ringkøbing-Skjern identify the more suitable sites according to the five case-study criteria introduced in Section 2, Table 1. Given the possibility that

Figure 3: The situation of the selected sites among the two optimal areas and production potential

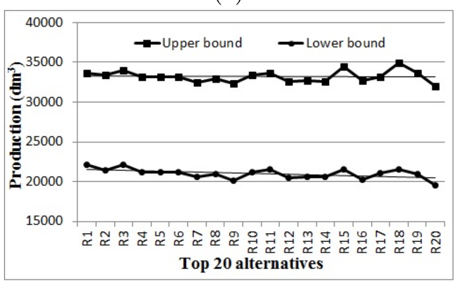




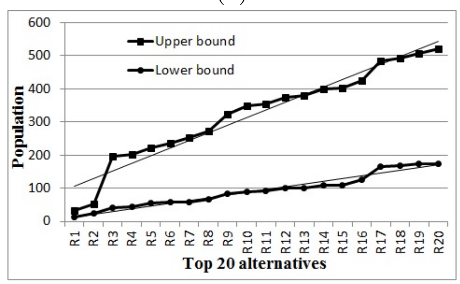
(a)



(b)



(c)



(d)

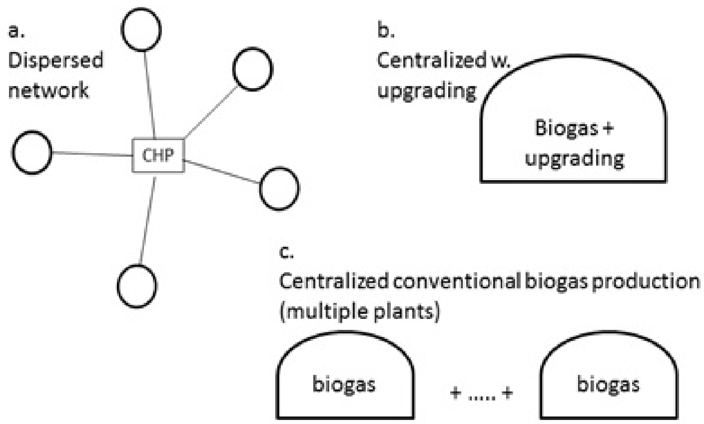
Figure 4: The impact of number of plants on the different criteria (a) Mean distance to heat plants (b) Mean distance to transport economic optimal zones (c) Mean production potential (d) Population density

the number of biogas plants that have to be built is previously specified, it is relevant to explore the impact of including one alternative after the other, following the final ranking of Table 4.

It can be seen from Fig. 4a, that the mean distance from the first site R1 to the heat plants is from 6.1 to 7.2 km, and it tends to decrease with the inclusion of more sites, right up to the first 15 locations, where it lies in between 3.3 and 4.5 km. In general, it decreases as long as more locations are considered, as shown by the trend line which finishes in between 3.5 and 4.6 km for the complete set of 20 sites. Something different occurs with the mean distance to the transport economic optimal zones and the mean production potential of Figs. 4b, 4c, where their trend line seems to remain constant along the inclusion of more alternatives. As it can be seen in Fig. 3, sites R11 and R18 are the ones that lie farther away from the transport economic optimal, while R6 is the one that is closest, which respectively explains the high and low peaks in Fig. 4b,. It is also noticed that sites R15 and R18 present higher production potential, which coincides with their proximity to the heat plants. Hence, the DM can examine the inclusion of different sites among the 20 top ranking, based on pertinent considerations aiming at an effective decision (a discussion on this issue is postponed for the next Section).

Finally, notice the relation between the number of sites and the population affected by their inclusion, from the third site R3 onwards, where the upper

Figure 5: Network layout designs: (a) Dispersed network, (b) centralized plant with upgrading and (c) multiple plants



bound for the population density increases from 200 people to over 500 per km^2 for all sites (see Fig. 4d). Given the low population density of Ringkøbing-Skjern, the absolute quantities seem low enough for obtaining general social acceptability, but the relative increment from R2 to R3 of more than 200% and the continuous increment that occurs afterwards, leads to take well into account the effects of including more sites on the general social acceptability. Focusing on the geographical results of this case study, see again Fig. 3, this aspect serves to explain the observed general closeness between the 20 sites, not only from a economic viewpoint (see the previous Section 4.1), but also from a social one, where the more concentrated the sites are (around a specific optimal area), the more social acceptability there is expected to exist.

5. Discussion

As seen in Table 4 and Figs. 4a-4d, the top 20 alternatives have particular strengths and weaknesses concerning their general suitability and the goals and restrictions that DMs have to consider to arrive to satisfactory decisions. Therefore, the decision process has to take into account the design of the biogas network layout. Such network layout refers to the interaction between biogas plants according to their type of production and production capacity, which at the same time influences the number of plants that have to be built. Until now in Denmark the centralized biogas production type (see Fig. 5c) has been the prevailing production design, but other network designs can be considered like e.g., a farm based dispersed network layout (Fig. 5a) or a centralized biogas production with upgrading (Fig.5b).

In Ringkøbing-Skjern a dispersed biogas network layout is currently under consideration (Fig. 5a), in which a number of large farms establish a farm based biogas production network, connected by gas pipes to a combined heat and power (CHP) plant. At the CHP plant, the biogas is incinerated and district heat and power is produced. Under this layout, biogas plants are located around an already existing CHP (functioning as biogas incineration hub), where the farm based biogas plants can be selected upon their planning suitability degrees, production potential (at farm level) and the population density in the vicinity of the farm. On the contrary, the distances to transport economic optimal zones should receive less importance, since the farm based biogas production requires no transport to and from other farms for collecting slurry. Instead, transportation costs for biomasses other than slurry have to be considered, since they are required to increase the drymatter content of the slurry in the biogas reactor (but it is beyond this study to consider potential demand for other biomasses).

Another possibility is to consider a centralized production network (Fig. 5b), which consists of a large biogas facility with subsequent upgrading of biogas to biomethane. This type of centralized biogas production with upgrading should not consider distance to heat plants, since the biomethane is pumped into the natural gas grid. Then, the upgraded biogas can be transported to gas costumers locally or in other parts of the country if needed. The biomethane can even be pressurized and used as transport fuel, which is an emerging technology in Denmark.

Finally, a conventional centralized biogas production network (Fig. 5c) can be considered. In this, the biogas is incinerated at a CHP producing power and district heating for local use. If this production layout is chosen, then multiple biogas plants can be built but their capacity depends on the amount of district heating supply that the CHP has to cover. Since 17 of the 20 highest scoring alternatives are located within an area of 60 km^2, the spatial competition between multiple plants is an important issue to address, since contracts are usually agreed upon on a one to one basis between farmer and biogas plant. Under this network layout design, all of the (A)-(E) criteria (see Table 1) have to be considered, where alternatives R1-R5 are particularly interesting since they have the highest suitability scores. If more biogas plants have to be included in the network, the final decision should further consider the results of a spatial competition analysis in order to avoid production inefficiencies or resource shortage due to poor resource planning (for a detailed analysis on the conditioned biogas production potential under spatial competition see [3]).

Taking into account the biogas network layout, the GAF methodology can be applied within the entire country, where different layouts can simultaneously exist, adding extra complexity to the decision problem. In doing so, it would be necessary to address the appropriateness of the given set of criteria for the location of biogas plants. This is due to e.g., the variation in local demand for district heating and the presence of competing technologies, such as geothermal heating or straw and wood chips for combustion.

6. Conclusions

The GAF methodology proposed here supports different DMs on the identification of suitable biogas plant locations, taking into consideration minimization of economic and social costs (distance to economic optimal and heat plants, population density), maximization of economic benefits (production potential) and legislative restrictions (municipality production plans). Besides, expert opinions on the relative importance of these criteria are aggregated for the joint exploitation of the geographical measurements, and the candidate sites are ranked under natural conditions of uncertainty/imprecision. The GAF methodology has been applied to the case study in the whole municipality of Ringkøbing-Skjern, providing a solid and reliable framework for understanding the decision problem and recommending suitable courses of action.

As further research, this methodology can be extended to include different energy technologies, where municipal solid wastes and industrial and agricultural by-products are utilized for energy production. Considering other potential biomasses and new technologies, decision support on the location of bioenergy facilities has to examine the impact of distinct network layout designs on the set of alternatives, the set of criteria, and the subjacent interactions among them.

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