A fuzzy approach for selection of best available techniques

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Abstract. Sustainable development is the most important challenge in recent years, and it is extremely important to save the environment, safety and well-being of lives now and future generations. In this regard, the role of environmental regulation methods aiming at the use of innovation-based green technologies is increasing. The modern regulation principles incentivize the implementation of best available techniques. Evaluating best available techniques is a difficult problem and requires taking into account numerous criteria. The application of optimization models offers an objectively based basis for reasonable decisions making. Hence, the design of new effective methods for determination of the best available techniques is an actual research direction. The problem of BAT estimation includes a variety of parameters whose values cannot be defined exactly, which defines their representation in terms of the theory of fuzzy sets. The present paper is devoted to the use of the fuzzy-based methods for the best available techniques selection process. The proposed methods are an extension of the information-mathematical toolbox for the solution of the selection problem of the best available techniques. Keywords: Best Available Technique, Multi-Criteria Decision Making, Fuzzy Number.

1 Introduction

Solving environmental problems is an important part of the principles of sustainable development. The use of clean technologies leads to a significant improvement in the quality of the environment [1]. The purpose of the concept of best available technologies (BAT) is to stimulate the introduction of such technologies. In the reference document "European Commission Background Paper 2006 on Integrated Pollution Prevention and Control by Economy and Cross-Media Effects" BAT is identified as

"the most effective and advanced stage in the development of activities and their methods of operation which indicates the practical suitability of particular techniques for providing the basis for emission limit values and other permit conditions designed to prevent and, where that is not practicable, to reduce emissions and the impact on the environment as a whole".

The BAT are used to prevent industrial pollution, in accordance with them the requirements for obtaining environmental permits for enterprises are determined. However, in the process of selecting BAT it is necessary to solve complex problems with ambiguous

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characteristics using expert assessments. As the authors [2] state, there is no one universal formal tool to support the analysis and the entire decision-making process at each stage of the BAT determination. However, the use of these tools provides an objective basis for decision-making.

The number of publications devoted to the problem of the BAT estimation is growing rapidly. For example, methodological approaches used to evaluate the BAT are considered in the review [3] where the steps to determine and apply BAT are derived. An overview of evaluation methods and a model of the overall technology selection process is presented in [4]. The model includes the following steps: Selection of evaluation criteria - Collection of information and data - Obtaining sustainability indicators - Normalization of indicators - Weighting of criteria - Comparison of options and selection of the best alternative - Analysis of results. This review presents current trends in BAT selection methods, describing the selection criteria, sources of information and the mathematical methods applied. However, the problem of improving the methods for determination of the BAT and developing new methods remains relevant [5].

The main approach to the determination of BAT is to use the multi-criteria decision-making (MCDM) methodology [6]. The problem of BAT selection is complicated by the lack of precise characteristics of technologies. The methodology of fuzzy sets theory provides an adequate account of uncertainty. A new direction in the evolution of multicriteria methods of decision making was given with the emergence of this theory. However, in the review [4] it is noted that fuzzy methods are rarely used. This paper focuses on the application of fuzzy approach at some steps of the BAT selection process. We summarize some of the results got in [7-10].

2 Materials and Methods

The characteristic feature of solving environmental problems is the need for compromise between various environmental, economic, socio-political criteria, conflicts of perceptions, interests and assessments. Therefore, the formal MCDM methodology is particularly efficient in this case [11].

Various criteria need to be considered when selecting the BAT. Environmental criteria include emissions and discharges, resources required, waste and energy inputs, noise, smells and other criteria. Economic criteria include payback period, net present value, investment, operating costs and other criteria. Technical includes space requirements, maintenance requirements, complexity of use and other technical criteria. Social includes health and safety impacts, new jobs and other criteria. Political includes legislative framework, standards, government support, and other criteria.

One of the key problems of the BAT selection is the adequate accounting of uncertainty. In the most cases, the decision-making process takes place under conditions of uncertainty, when the goals and constraints are not exactly known. A large amount of information from several independent sources needs to be analyzed to determine alternative emission levels and operating costs [12], which is a serious problem [5]. These values largely depend on expert estimation [13], they cannot be set in a precise way, reference books define ranges inherent in the best available technologies. This determines for the selection of BAT the adequacy of using the fuzzy set theory apparatus [14]. However, fuzzy multicriteria decision-making methodology for this task is applied rather rarely, we can highlight, for example, [15-17].

The values of a number of parameters can be represented in the terms of fuzzy set theory. This permits to analyze several alternative solutions and to find trade-offs. This paper proposes the application of fuzzy multi-criteria decision making procedure. It allows to operate with unformalized data and subjective judgments of experts. Environmental and economic criteria can be represented by fuzzy numbers, while technical, social and political criteria can be represented by linguistic variables.

3 Fuzzification of Criteria

3.1 Fuzzification for Environmental Criteria

Entropy estimates are used to phase-in the environmental parameters. Emissions and resources for each of the alternative technologies must be quantified. First, the list of significant input and output flows (such as, for instance, consumed resources, emissions, and discharges of pollutants, waste amounts and energy expenses) and the magnitude of these flows should be estimated for each available technology. The general methodology of BAT selection assumes comparison of data from various independent sources [18]. These data can be obtained from monitoring of operating facilities, from research reports, calculation data, information from equipment manufacturers, etc. Industrial enterprises that provide data on their technologies, equipment, data on pollutant discharges and emissions, waste amounts and other environmental and economic indicators are the main sources. Data from different sources may differ, particularly in the initial phases of technology use. It is necessary to identify these data during periods of time when technologies are in stable modes and the data can be reliably used to compare BAT.

The input and output data are a series of measures taken at regular intervals [8]. To determine the stable values of the criteria, we analyze the information related to each alternative technology.

The following notations are used: d is the number of alternative technologies; k is the index of technology; $k = 1, \dots, d$; L^k is the number of sources of information on technology k; l is the index of the source of information; $l = 1, \dots, L^k$; T is the number of periods during which information from sources is available; t is the period index; $t = 1, \dots, T$; n is the number of input and output flows (characteristics, criteria) of the technology; i is the flow number; $i = 1, \dots, n$; $c^{ik}{}_{lt}$ is the value of the ith characteristic of technology k, obtained from the lth source in period t; $i = 1, \dots, n$; $l = 1, \dots, L^k$; $t = 1, \dots, T$.

For any technology k and fixed characteristic i, we can define the minimum and maximum values for the obtained set of characteristics, as follows:

$$c_t^{ik}{}_{max} = max\ \{c^{ik}{}_{lt} \mid l = 1, \dots, L^k\ , t = 1, \dots, T\};$$

$$c_t^{ik}{}_{min} = min\ \{c^{ik}{}_{lt} \mid l = 1, \dots, L^k\ , t = 1, \dots, T\}.$$

The whole range of obtained values $[c_t^{ik}{}_{max}\ ;\ c_t^{ik}{}_{min}]$ is divided into F equal intervals where F is assigned by the decision maker. For each interval we define the number of events $C^{ik}{}_f$ for which the value of $c^{ik}{}_{lt}$; $i = 1, \dots, n; f = 1, \dots, F$; $l = 1, \dots, L^k$; $t = 1, \dots, T,$ is within the bounds of the interval f. The number of values $\{c^{ik}{}_{lt}\ \}$ is $K = L^k\ T$. The relative frequency of events consisting in the fact that the value of the characteristic i belongs to the interval f during T periods is defined as

$$p^{ik}{}_f = C^{ik}{}_f /K = C^{ik}{}_f /(L^k\ T).$$

The entropy of the values of the characteristic i of technology k over T periods is defined as

$$H^{ik}{}_T = -\sum_f p^{ik}{}_f \log p^{ik}{}_f.$$

At the next period $T + 1$ the entropy value takes the value $H^{ik}{}_{T+1}$. The data flow can be considered stable if the entropy value for h periods changes not significant

$$| H^{ik}{}_{t+1} - H^{ik}{}_{t} | < \varepsilon; \ \ t = (T - h + 1), \dots , T,$$

where h and ε are defined expertly. If entropy fluctuations are significant, the technology cannot claim to be the best.

Finally, we obtain the interval of stable values of the parameter. The minimum and maximum values of the last period determine the interval $[c_{ik}{}^{min} ; c_{ik}{}^{max}]$. It is the support of the fuzzy number $\underset{\sim}{c}_{ik}$, representing the characteristic under consideration. To determine the most possible value of the criterion c_{ik} which characterizes the technology k over the flow i we use the Hurwitz criterion:

$$c_{ik}{}^{pos} = \lambda \, c_{ik}{}^{max} + (1 - \lambda) \, c_{ik}{}^{min},$$

where

$$c_{ik}{}^{max} = max \ \{c^{ik}{}_{lT} \mid l = 1, \dots , L^{k}\};$$

$$c_{ik}{}^{min} = min \ \{c^{ik}{}_{lT} \mid l = 1, \dots , L^{k}\};$$

λ is the Hurwitz criterion, $0 \le \lambda \le 1$.

As a result, the parameter can be adequately represented by a fuzzy number with a suitable for computer implementation triangular membership function $(c_{ik}{}^{min} , c_{ik}{}^{pos} , c_{ik}{}^{max})$. In this way, the fuzzy estimates $\underset{\sim}{c}_{ik}$ of each flow for each technology are successfully determined, $k = 1, \dots , d$; $i = 1, \dots , n$.

3.2 Fuzzification for other criteria

The economic criteria e_{ik} are defined similarly to the environmental criteria, $k = 1, \dots , d$; $i = 1, \dots , m$; m is the number of the economic criteria. Technical, political and social criteria are evaluated and determined by the decision makers based on linguistic variables. The linguistic terms are represented as triangular fuzzy numbers and are ranging from "*very low*" to "*very high*" (see Fig. 1).

The information of weight criteria is of great importance [19]. To compare alternative technologies decision makers need to determine the weights of each criterion. The weights can be obtained by using any of the fuzzy modifications of expert methods. Determining the weights is subjective and requires expert agreement. In many cases, experts cannot determine the weights by exact numerical values. It is more convenient to use verbal statements instead of numerical values, so we propose to represent the values of weights by linguistic variables.

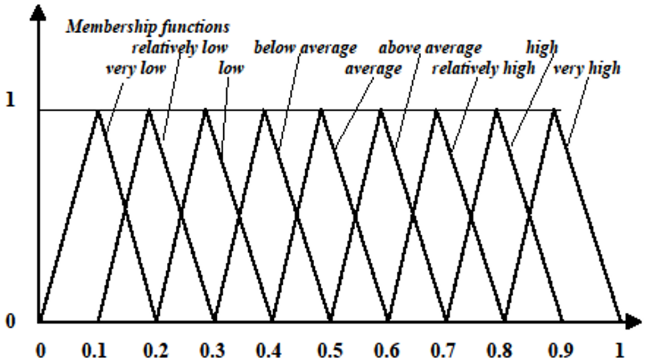

Fig. 1. Set of linguistic terms.

Triangular membership functions defined on the universal set represented by the interval [0, 1] are convenient for presenting linguistic variables. Fuzzy weighted aggregation operators can be used for aggregation of expert evaluations of criteria weights [20].

4 Selection of the Best Alternative

Each of the five groups of criteria, which we will call the criteria of the first level, has its own partial criteria, which we will call the criteria of the second level. A formal description of the fuzzy problem-solving method of the BAT choice is presented below. Operations with fuzzy numbers are defined, for example, in [20].

We will use the new notation in the following. A set of d technologies is evaluated by 5 groups of first-level criteria, $g = 1, \ldots, 5$. Each group g has n_g criteria of the second level. m experts determine the estimate for each criterion of the second level for each technology.

The evaluation of the second level criterion i related to the first level criterion g is carried out by expert j for technology k by minimum, maximum and highest possible values of indicators, which allows us to propose their natural representation by fuzzy numbers r_{kgij}; $k = 1, \ldots, d$; $g = 1, \ldots, 3$; $i = 1, \ldots, n_g$; $j = 1, \ldots, m$ with triangular membership functions.

The weight of criterion i is evaluated by expert j with a linguistic variable converted to a fuzzy number w_{gij}; $g = 1, \ldots, 5$; $i = 1, \ldots, n_g$; $j = 1, \ldots, m$.

Weights and estimates are aggregated taking into account the experts' opinions. There are various methods for this [18], the simplest aggregation procedure is as follows:

$$w_{gi} = (w_{gi1} + \ldots + w_{gim}) / m;$$

$$r_{kgi} = (r_{kgi1} + \ldots + r_{kgim}) / m;$$

$k = 1, \ldots, d$; $g = 1, \ldots, 5$; $i = 1, \ldots, n_g$.

The values of the criteria are normalized to make them comparable using a fuzzy version of the linear scaling method.

$$\underline{r}_{kgi} = r_{kgi} / (r_{1gi} + \ldots + r_{nggi});$$

$k = 1, \ldots, d$; $g = 1, \ldots, 5$; $i = 1, \ldots, n_g$.

The next step is to normalize weights:

$$\underline{w}_{gi} = w_{gi} / (w_{g1} + \ldots + w_{gng});$$

$g = 1, \ldots, 5$; $i = 1, \ldots, n_g$.

Then the complex evaluations of groups of criteria for each technology are determined:

$$R_{kg} = \underline{w}_{g1} \, \underline{r}_{kg1} + \ldots + \underline{w}_{gn} \, \underline{r}_{kgng};$$

$k = 1, \ldots, d$; $g = 1, \ldots, 5$.

The weights of the first level criteria W_g are determined similarly to the weights of the second level criteria, which are then also normalized:

$$\underline{W}_g = W_g / (W_g + \dots + W_5);$$

$g = 1, \dots, 5.$

At last, a comprehensive assessment of the technology is determined:

$$R_k = \underline{W}_1 R_{k1} + \dots + \underline{W}_5 R_{k5} \ ;$$

$k = 1, \dots , d.$

In the final step, the best of d alternative technologies is selected.

Various formal methods are used to select BAT, such as AHP (Analytic Hierarchy Process), ANP (Analytic Network Process), TOPSIS (Technique for Order Preference by the Similarity to the Ideal Solution), ELECTRE (ELimination and Choice Expressing REality), PROMETHEE (Preference Ranking Organization METHod for Enrichment of Evaluations), WSM (Weighted Sum Method) [4]. Each of them has its strengths and weaknesses, and variants of methods improvement are proposed for real tasks. One of the most popular methods is TOPSIS [21]. We use the TOPSIS method in a fuzzy formulation [22]. The positive ideal solution is defined as:

$$R^+ = \underline{W}_1 R^+_{k1} + \dots + \underline{W}_5 R^+_{k5}$$

where

$$R^+_{kg} = max \ \{R_{ki} \mid g = 1, \dots , 5 \mid k = 1, \dots , d\}.$$

The negative ideal solution is defined as:

$$R^- = \underline{W}_1 R^-_{k1} + \dots + \underline{W}_5 R^-_{k5}$$

where

$$R^-_{kg} = min \ \{R_{ki} \mid g = 1, \dots , 5 \mid k = 1, \dots , d\}.$$

For each alternative, the Hamming distances from the positive ideal solution $d(R_k , R^+)$ and negative ideal solution $d(R_k , R^–)$ are determined, $k = 1, \dots , d$. TOPSIS rank indexes are calculated as:

$$CC_k = d(R_k , R^–) / [d(R_k , R^–) + d(R_k , R^+)]; \ k = 1, \dots , d.$$

The best alternative is the b alternative with the greatest value:

$$CC_b = max \ \{CC_k \mid k = 1, \dots , m\}.$$

Hierarchical chart for the problem of the BAT selection is shown in Fig. 2.

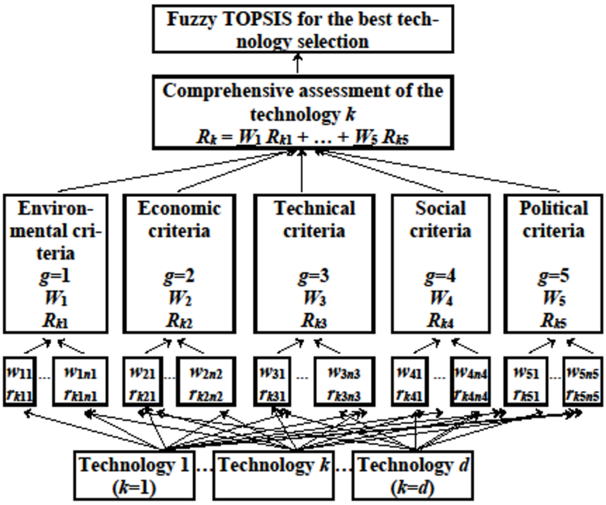

Fig. 2. Hierarchical chart for the problem of the BAT selection.

5 Conclusion

This paper presents the fuzzy approach for the stages of the BAT assessment. This complex task must take into account many environmental, technological, economic, political and social criteria. Notice that the BAT estimation process is largely based on the intuition, experience and mentality of the decision makers and cannot be fully formalized. However, the selection process is greatly facilitated by the use of mathematical and instrumental tools that create the framework and information structure for final decision-making, particularly for large-scale problems.

One of the main conditions for the correct selection of tools for decision-making on the BAT is to adequately address uncertain input data. The fuzzy approach is used as a basis of the quantitative method for estimating, analyzing and processing information that allows determining the stable values of criteria for alternative technologies that can be used for the BAT comparison and selection procedure. Uncertainty of initial data creates serious problems for decision making for selecting BAT. We propose a quantitative method of information evaluation to determine the stable values of criteria, it allows to objectively represent the parameters of the problem in terms of fuzzy sets. We represent environmental and economic criteria by fuzzy numbers, and technical, political and social criteria by linguistic variables. The fuzzy TOPSIS method is proposed to compare and select alternative technologies. In contrast to previously published works, which use fuzzy methods, but only the sampling parameters are represented in terms of fuzzy sets, and at certain stages they are transformed into crisp values, we do not perform defuzzification of the criteria and weights at all steps of the selection process.

The fuzzy approach was tested with numerical examples and showed that the proposed procedure is reliable and effective. It leads effective computational procedures and provides stable results. The suggested methods is an extension of information and mathematical tools for solving environmental problems. We plan to use this approach to other MCDM problems, focusing on practical issues of environmental tasks.

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