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An Intelligent Decision Support System for Environmental Impact Assessment of Industrial Projects

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Abstract: Environmental Impact Assessment (EIA) of industrial projects is a typically ill-structured, multi-aspect, multi-criterion decision making problem, in which usually not all input relevant factors are known, and the relationships between these factors and the direct impact on environmental elements can not be stated or formulated exactly. The assessment can have several dimensions like air pollution impact, water pollution impact, etc. Each dimension has its own set of homogenous variables. This paper presents a modular decision making solution for treating the complex ill-structured EIA decision problem. The proposed solution is an intelligent environmental decision support system (EDSS) that makes use of human expertise's and fuzzy logics in assessing the environmental impacts of the proposed or existing industrial projects. It consists of multiple fuzzy expert systems (FESs), each of which contains the homogenous knowledge's and expertise's relevant to a one environmental dimension. Simple and efficient heuristics are introduced for integrating FESs within the proposed EDSS.

Keywords: Environmental Impact Assessment; Environmental Decision Support; Fuzzy Expert Systems; Analytical Hierarchy Process; Binary Group Decision-Making.

1 INTRODUCTION

All industrial and development projects can affect their surroundings. An EIA is an assessment of the likely positive and/or negative influence a project proposal may have on the environment. The problem typically involves: huge quantities of data to manipulate, low quality of data (uncertainty, measurement errors, missing data), different spatial and temporal scales, dynamic and stochastic behavior, and being at the crossroad among many disciplines/domains, and so many qualitative or subjective factors. In fact, the review of literature has demonstrated that the development of environmental decision support systems (EDSS) is rapidly progressing [Matthies, 2007]. Some of the reported literature concentrated on the role of Artificial Intelligence like [Cortès et al., 2000; Sokolova & Fernandez, 2008]. Recent literatures has revealed the focus on Group Decision Making and Consensus [Liu and Wirtz, 2006; Turon et al., 2007], and the utilization of fuzzy logics [Liu and Wirtz, 2006 ; Nasiri and Huang, 2008] as appropriate to the nature of EIA decision problems. Matthies et al. [Matthies et al., 2007] discussed the background of recent developments in EDSS and summarized a selected set of papers that were presented at the 2nd Biennial Conference of the International Society of Environmental Modeling and Software (IEMSS 2004). They pointed out that there is a general tendency toward better utilization of interdisciplinary data, integration and visualization of temporal and spatial results.

The most common approach of EIA is Leopold matrix [Leopold et al., 1971]. The system consists of a matrix with columns representing the various activities of the project, and rows representing the various environmental factors to be considered. The intersections are filled in to indicate the magnitude (from -10 to +10) and the importance (from 1 to 10) of the impact of each activity on each environmental factor. However, Gilberte White [White, 1972] pinpointed several limitations of the matix. He stated that Leopold matrix contains no provision for indicating uncertainty resulting from inadequate data or knowledge. He also pointed out that the Leopold matrix does not provide explicit criteria for assigning numerical values to weights of impacts. Moreover, the synthesis of the predictions into aggregate indices is not possible. Therefore, given the limitations of Leopold Matrix, the EDSS proposed in this paper will enable elimination of such limitations, first through employing fuzzy logics for handling uncertainty. Second, it consistently enables for inferring the environmental impacts of the project's activities with respect to various environmental factors through decision logics representing the knowledge and expertise's human environmental experts, and finally enables synthesizing the main impact magnitudes corresponding to the main environmental factors into an overall impact, which was not possible with Leopold matrix approach. It should be noted that there is a basic difference between EIA and the LCA (ISO 14042) methodologies in that the former is a framework for identifying, predicting, evaluating, and mitigating the biophysical, social, and other effects of proposed projects or plans and physical activities, whereas as the later is a method of accounting the environmental impacts of a product, service, or process over the course of its life cycle from extraction of materials to disposal or reuse of the final product.

This paper is organized as follows. Section 2 presents the proposed modular and intelligent EDSS. In section 3, the basic numerical scale for judging environmental impact magnitudes is established, and the Analytical Hierarchy Process (AHP) is proposed as a method for computing weights of environmental factors and systems. Section 4 explains the decision procedure using the proposed EDSS and gives illustrative examples.

2 THE PROPOSED EDSS FOR EIA

2.1 The Rationale for Modular and Collective EDSS

Turon et al. [Turon et al., 2007] stated that the judgments of many will usually prove superior to the judgment of one. One kind of critical decision making problems is the binary or Yes/No decision making. The classification of environmental impact of an industrial project into either "Positive" or "Negative" is one typical instance of such critical decision problems. Integrating multiple intelligent decision support or expert systems is considered particularly useful in obtaining high quality, comprehensible and reliable decision solution. Such integration is justified when a complex problem in hand has multiple aspects (e.g., the EIA) and requires multiple expertise's to cope with its ill-structuredness and ambiguity. Sometimes the integration is accomplished for sake of reliability. However, still some other reasons behind independence amongst expert systems are: cohesion of knowledge units, control and decision responsibility, avoidance of knowledge interaction and mutual influence, modularity in decision analysis and explanation, sensitivity of aggregate knowledge (sometimes), consistency in handling relationships and reasoning. Also, besides the above pragmatic reasons, building small and separate expert systems can justify for operational inefficiency usually exhibited with huge and cumbersome large-scale expert system. Now, based on the above reasons, our proposed systems will be composed of multiple fuzzy expert systems (FESs), as appropriate to the nature of EIA decision making context. Next section introduces the architecture of the proposed EDSS.

2.2 The Architecture of the Proposed EDSS

The proposed EDSS consists of multiple environmental decision making units, the FESs, as shown in figure 1. In such configuration, FESs are connected in parallel. Each FES provides its output on whether the corresponding environmental impact is positive or negative. Each individual system accepts different sets of relevant environmental input factors. Although the idea of integrating multiple decision making systems is not new and classic, combining the outputs of multiple FESs is a new and has been first introduced in [Aly & Vrana, 2006]. Multiple criteria could be processed within the decision logic of each, or each FES by itself could represent a one judgment criterion. The proposed decision making system is well suited for two different decision making situations. In the first situation different knowledge sources (i.e., FESs) each of which corresponds to different environmental dimensions (e.g., air pollution, water pollution, etc.). The second situation involves similar knowledge sources all specialized in a one environmental issue, like air pollution, each of which holds different skills, tools, or techniques. In the first situation, the final consolidated output of the given FESs is obtained through aggregation of their final impact values, since all knowledge sources are necessary to judge the overall environmental impact of the proposal, whereas, in the second case, a simple consensus heuristic is to be used for combining FESs' outputs, because the inclusion of multiple knowledge sources aims to enhance the reliability, specially for such ill-structured and ambiguous decision problems. Next section explains in brief the internal components of each FESs.

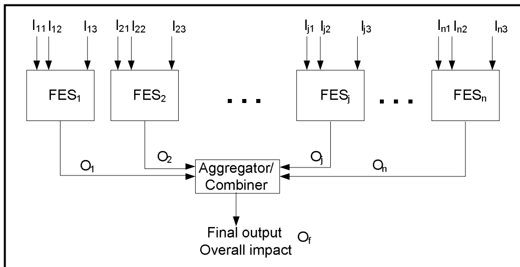

Figure 1. The architecture of the proposed EDSS.

2.3 The Internal Structure and Processing of Modular Decision Making Units

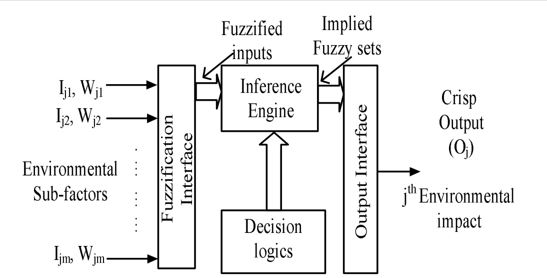

Figure 2. The internal structure of environmental FESs.

As described previously, the proposed EDSS consists of multiple FESs. Every FES processes the influence of a subgroup of input environmental factors, with respect to one main environmental issue like Air pollution, or soil contamination, on environmental impact. The standard FES (see figure 2) consists of four components: a fuzzification subsystem, a knowledge-base, an inference mechanism, and a defuzzification subsystem. The fuzzification subsystem converts the values of the quantitative and qualitative environmental sub-factors into fuzzy sets. The knowledge base contains the decision making logics containing the experts' knowledge about how to convert the values of sub-factors into an environmental impact regarding one environmental issue of main factor. However, it could contain an empirical knowledge as well. The inference mechanism match the current values of input factors with the set of applicable rules, and then infer the implied fuzzy set of each rule. Finally, the defuzzification subsystem converts the implied fuzzy sets into crisp value expressing the Positive/Negative alternatives. The special concern put on FESs in general is attributed to its wide applicability and use due to its capability to treat vagueness, and subjectivity. More description of the FES can be found in [Kilagiz et al., 2004]. Next section explains how to quantify both environmental impacts' magnitudes and importance's of FESs.

3 THE JUDGMENT SCALE AND THE IMPORTANCE'S OF ENVIRONMENTAL FACTORS AND IMPACTS

The proposed scale (figure 3) for quantifying the environmetal impact outputs of the indivdual FESs is same like that of the Leopold matrix. The magnitudes of environmetal impacts is quantified within the range [-10, +10], where -10 indicates sharp "Negative" impact, +10 indicates sharp "Positive" impact, and 0 means "Non-biased" value. Intermediate values reflect the bias toward either two options. The same scale is to be used as the universe of discourse for the implied or output fuzzy sets within each FESs. Generally, positive values of impact indicate or signify benefits caused by the assessed project, whereas negative values indicate harm caused by the project. On the other hand, in order to reflect the relative importance of every FES in judging the environmental impact, and the importance's of the environmental factors as well, the most commonly used decision-aiding tool, the Analytical Hierarchy Process (AHP) [Saaty, 1980] is to be used to compute the absolute weights of different environmental factor, and the weights of the individual FESs, too. In AHP, the decision maker carries out simple pair-wise comparative judgments, which are then used to develop overall priorities for ranking alternatives, factors or criteria. These priorities or weights are normalized within the computations of the AHP. The reader may refer to [Saaty, 1980] for more details about AHP and its computational procedure. Next section will describe the basic mechanism for integrating the FESS within the proposed intelligent EDSS.

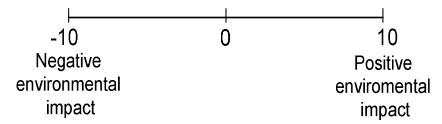

Figure 3. The numerical scale for quantifying environmental impacts.

4 THE DECISION MAKING PROCEDURE

There are two decision making situations to be treated in this article. In the first decision making situation, several different knowledge sources or expertise's (FESs) each of which holds different knowledge about different environmental dimensions, integrated for sake of comprehensibility. Consequently their individual environmental output impacts should be aggregated. On the other hand, in the second situation, we have several knowledge sources (FESs) having same or equal knowledge but different tools, skills or techniques, integrated for sake of enhancing the reliability of the final decision solution or overall impact. For more explanation of difference between knowledge's combination and aggregation, the reader may refer to [Aly & Vrana, 2006]. It should be noted that the utilization of evidence theory combination rule could be exploited but we well confront a problem of estimating the aggregate belief in the knowledge contained in each FESs. Next two subsections will introduce a decision making procedures for both cases.

4.1 A Heuristic for Aggregating the Impacts of Different Environmental Knowledge Sources

Here, final overall environmental impact is obtained through aggregating the environmental impact of the individual FESs corresponding or pertaining to each environmental issue using the weighted average, and taking into account the weights of each FESs computed via the AHP. The aggregation is formally stated as follows:

Let O_j : the output impact for the j[th] FES.

W_j : the weight of the j[th] FES.

O_t^- : a threshold value for negative environmental impact. This threshold value is optional and could be set according to the opinion of field experts and decision analysts.

Step 1: Compute the weights of FESs using AHP

Step 2: Check the negative output impacts against the threshold (O_t^-):

$\forall j$ IF $O_j \leq O_t^-$ THEN $O_f = O_t^-$; reject project; otherwise go to step 3.

This means that if the output impact of any FES exceeds the negative threshold, then the project should be rejected without any concern to other outputs. Other decision policy could be established based on the opinions of field experts and decision analysts.

Step 3: Establish a total numerical scale from within an arbitrary range from –S to +S value, to represent the decisive degree between "Positive" and "Negative" decisions. The value -S corresponds to "Negative", and the value +S corresponds to "Positive". The middle value of such total scale is zero.

Step 4: Apportion the total numerical scale established in the previous step into smaller numerical scales allocated to every FES in proportion to its computed weights, as follows:-

$$S_j = w_j * 2S \qquad \forall j \tag{1}$$

Where,

S_j: is the total range for output scale of the j^{th} FES.

Then, the crisp output of each j^{th} FES should be produced within the allocated numerical scale, from 0 to S_j. Proportionality could be used to convert outputs within the range [-10, +10] into the partitioned scales, as another options.

Step 5: Given the crisp output of each FES, aggregate expertise's by summing all crisp outputs to given the finally aggregated group output, O_f (eq. 2):

$$O_f = \sum_{i=1}^{n} Oj \tag{2}$$

Then, the final output is judged as either "Positive" or "Negative" as follows:-

If $O_f > 0$, then the final group decision is "Positive"; accept (continue) project.

If $O_f < 0$, then the final group decision is "Negative"; reject (stop) project.

If $O_f = 0$, then the final group decision is "Non-biased"; optional, up to experts and decision analysts opinion. Stop.

Example 1:

Suppose that given a proposed industrial project involving some mechanical industrial operations and chemical process. The project outputs its chemical waste to a river, whose water is used in irrigation. Before actual construction and operation phases, it is required to assess the overall environmental impact of the project's industrial activities on the surrounding environment on several dimensions that leads finally to a decision of whether to undertake the project or not. There are four environmental aspects to consider: air pollution, noise/vibration, water pollution and soil contamination impacts. Every environmental aspect includes several input factors, may be quantitative or qualitative. Some of these factors could have uncertain or vague values. Moreover, due to ill-structuredness, the relationship between these inputs factors and the direct impact on the elements of the environment is not fully grasped. Accordingly, our proposed decision making systems here is appropriate. Therefore, four FESs corresponding to the four environmental aspects could be constructed; namely, air pollution expert system, noise/vibration expert system, water pollution expert system and soil contamination expert system. Each FES processes a homogenous group of input factors or variables as relevant to one environmental aspect. Every system contains the expertise's, and knowledge of several experts specialized in certain environmental aspect. Let us suppose that the output impacts and weights of each FES were as follows:

- Air Pollution Expert System (FES_1) O_1 = -8, W_1 = 0.51
- Noise/vibration Expert System (FES_2) O_2 = 0, W_2 = 0.22
- Water Pollution Expert System (FES_3) O_3 = -2, W_3 = 0.26
- Soil Contamination Expert System (FES_4) O_4 = +6, W_4 = 0.01

Now applying the above procedure:

Threshold check in step 2 fails. Then, we proceed to step 3. Now, we have the outputs values of impacts all evaluated within [-10, +10]. Applying step 3 we establish a total scale arbitrarily selected as the sum of indivdual scale, [-40, +40]. Here, S equal 40, then we partition this total scales into four smaller ones to determine the judgmental quota or space for each environmental dimension according to its weight. Using proportioality, the total ranges for allocated scales are: 40.8, 17.6, 20.8 and 0.8, for FES_1, FES_2 , FES_3 and FES_4 respectively, and converted outputs becomes as follows: -16.32, 0, -2.08, +0.24. The aggregation of these output using equation 2 gives O_f = - 18.16 < 0, thus the final decision is "Negative"; reject (stop) project. It should be noted that a threshold could be established also on the value of the O_f, and thus if the negative impacts is less than that threshold, only the project is rejected.

4.2 A Consensus Heuristic for Combining the Impacts of Knowledge-equal Sources

Sometimes the outcomes and performance of the proposed project is affected by the occurrence of some uncertain future events. In such situation, it is adequate to construct multiple FESs, each of which specialized in same areas, but utilize different tools or techniques. The final overall impact is based on combining the decision outputs of the participating expert systems rather than aggregating them, since each FES could solely perform the decision making task, but they are accumulated for reliability. Below, we propose a simple consensus-based heuristic that makes the final decision. In addition to the notations of the outputs and weights used in previous heuristic, Let two simple indicators defined as follows:-

- The Percentage of Class Voting's: the fraction of voting's given to certain class (Positive, Negative or Non-biased) = Number of Class voting's / Total number voting's.
- Sum of weights of voting's: the sum of weights of voting's given to a class

Based on the above definitions, we have six magnitudes: Percentage "Positive" voting's (*%PV*), Percentage "Negative" voting *(%NV*), Percentage "Non-biased" voting (*%NBV*), Sum of weights of "Positive" voting's (*SWPV*), Sum of weights of "Negative" voting's (*SWNV*) and Sum of weights of "Non-biased" voting's (*SWNBV*). Thus, High value of (*%PV*) means that there is a considerably high degree of consensus or voting's dominance assigned to "Positive Impact" decision option, and so on. Also, similarly, high value of SWPV means that there is a considerably high degree of weight dominance level that imposes undertaking the "Positive" direction, and so on.

Now, the steps of the aggregation heuristic are as follows:

Step 1: Compute weights of Individual FESs using AHP (W_i)

Step 2: Check the extreme values of outputs impact:
$\forall j$ IF O_j =10 THEN O_f = 10; accept project; Stop.
$\forall j$ IF O_j =- 10 THEN O_f = -10; reject project; Stop.

The rationale for rules above is that any expert system whose expertise exhibits complete bias to any one of the two alternatives, and then we should adhere to such emphasized opinion of such recognized expertise.

Step 3: Attributing outputs:

Every FES's impact judgment, O_i, is attributed to one of three classes or consensus sub-group depending on whether or not this value is above, below or at the zero:
Condition 3.1: IF $O_i > 0$, THEN O_i is attributed to "Positive" class.
Condition 3.2: IF $O_i < 0$, THEN O_i is attributed to "Negative" class.
Condition 3.3: IF $O_i = 0$, THEN O_i is attributed to "Non-biased" class.

Step 4: Preliminary checking**:** the heuristic is to be terminated because of either high voting's or weights dominance levels under the following two conditions (otherwise, go to step 3):-

Condition 4.1: IF max*{%PV, %NV, %NBV}* ≥ 75 %, THEN there is a high degree of voting's dominance level and is given by the class argument of max*{%PV, %NV, %NBV}*(arg max{*%PV, %PV, %NBV*}). Stop. Otherwise Go to step 5

Condition 4.2: IF max {*SWPV, SWNV, SWNBV*} ≥ 0.75, THEN a high degree of weighting dominance level and the DCA is given by the class argument of max{*SWPV, SWNV, SWNBV*}(arg max {*SWPV, SWNV, SWNBV*}). Stop. Otherwise Go to step 5

Note: arg max {*SWPV, SWNV, SWNBV*}or arg max{*%PV, %NV, %NBV*}gives the decision class which has either maximum voting's or weights dominance levels respectively.

Step 5: Compute the Weighted Arithmetic Mean of Impacts (WAMI) for the given output impacts:

$$WAM\ I = \sum O_j\ W_j \qquad (3)$$

Step 6: Interpret the value of AM into an overall positive or negative impact as follows:

Condition 4.1: IF the *WAMI* < 0 (negative overall impact), then project must be rejected or stopped Stop.

Condition 4.2: IF the *WAMI* ≥ 0, then project can be undertaken or continued. Stop.

Example 2

Suppose that it is required to evaluate whether an existing nuclear power plant will have a positive or negative impact on the Ozone depletion after 25 years from now. It is obvious that the decision answer is influenced by some uncertain future events and outcomes, pertaining to both elements of environments and the operational performance of the plant. Here, again it is difficult to exactly state all input factors or formulate their relationships with impacts after 25 years. Therefore, one effective solution is to rely on the multiple expertise's in order to cope with such ambiguity to enhance reliability. Again, our proposed system of multiple FESs fits here. Suppose that relevant to the industrial context and considered environmental dimension, a set of five expertise's factors and techniques specialized in Ozone depletion environmental issue. So, we construct five corresponding FESs. Every FES includes the expertise's and tools of subset of environmental experts or scientists, and manipulate its own set of relevant input factors. Then, every FES outputs its judgment, within -10 to +10, about whether the impact of the project after 25 years will be positive or negative. Now, suppose that the weights computed via AHP, and the output judgments of the systems were as follows:-

- FES_1 $O_1 = 0$, $W_1 = 0.2$
- FES_2 $O_2 = -2$, $W_2 = 0.22$
- FES_3 $O_3 = 0$, $W_3 = 0.32$
- FES_4 $O_4 = 6$, $W_4 = 0.01$
- FES_5 $O_5 = -9$, $W_5 = 0.25$

Now, the steps of the consensus heuristic are as follows: Extreme values check in step 2 fails since $O_j \neq \pm 10$ for $\forall\ j$. step 3 attributes output impacts as follows:
Positive class = {O_4 , O_5}, Negative class = {O_2}, Non-biased class = {O_1 , O_3}.
Application of step 4 does not reveal any voting's or weights dominance levels. Then, consensus could not be detected, and the last option is averaging using equation 3:

$$WAMI = \sum O_j\ W_j \quad = 0\ (0.2) + -2\ (0.22) + 0\ (0.32) + 6\ (0.01) + -9\ (0.25) = -2.18$$

Since the *WAMI* gives negative, the impact of the project after 25 years on the Ozone depletion is considered harmful.

5 CONCLUSION

The article has presented a modular and intelligent decision making systems for coping with ill-structuredness and uncertainty confronted in EIA. The presented approach improves decision process in this area and overcome some of the limitations of most common Leopold Matrix approach, through its ability to manipulate vagueness and uncertainty, and the ability to synthesis the impacts of the large number of factors into an overall impact in a logic and simple way. The proposed system also relies on the efficient human expertise's control, which is an unequaled solution to complex ill- structured decision problems. The system also avoids the operational limitations of having a single, huge and slow expert system. Finally, the proposed research could be exploited similarly in approximating vagueness and treating ill-structuredness within the LCA decision making.

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