Decision Support Systems 74 (2015) 135–149

Contents lists available at ScienceDirect

Decision Support Systems

journal homepage: www.elsevier.com/locate/dss

A novel entropy-based decision support framework for uncertainty resolution in the initial subjective evaluations of experts: The NATO enlargement problem

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ARTICLE INFO

Article history:
Received 24 April 2014
Received in revised form 1 April 2015
Accepted 2 April 2015
Available online 11 April 2015

Keywords:
Decision support framework
Entropy
Subjective expert evaluations
Incomplete information
Uncertainty
NATO

ABSTRACT

We introduce a novel decision support framework that allows decision makers (DMs) to assess the informativeness of a ranking of alternatives provided by different experts and to extrapolate additional evaluations based on the distributional bias and entropy inherent to those received from the experts. In the proposed framework, expert analysts rank several alternatives within opportunities versus threats space of potential evaluations. The resulting rankings of alternatives vary among experts due to differences in the set of evaluation criteria chosen and to the subjective weights assigned by the experts to the criteria considered. As a result, DMs observe biases in the evaluations provided by the experts and variations in the degree of informativeness among alternatives. Thus, DMs must use the information available to them to assess the reliability of the ranking obtained from the experts' evaluations. In this regard, the distributional bias generated by the evaluations received will be used to define the dynamic structure of an algorithm that allows DMs to extrapolate additional expected evaluations and modify the initial ranking proposed by the experts accordingly. At the same time, the entropy generated by the evaluations will be used to validate the reliability of the resulting rankings and to determine the stopping rule for the data generating algorithm. A numerical example based on the North Atlantic Treaty Organization (NATO) membership enlargement problem is presented, where several teams of experts provide different evaluations on a set of applicant countries. A battery of Monte Carlo simulations has been performed, and alternative biased approaches have been followed. The rankings obtained have been compared with those resulting from our framework.
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1. Introduction

In this study, we introduce a novel decision support framework that allows decision makers (DMs) to assess the ranking of alternatives provided by different experts and gain additional information by taking into account the distributional bias and entropy inherent to the decision making process. The high degree of subjectivity inherent to the judgments of experts when providing decision support has been consistently analyzed in the systems literature [1], particularly when dealing with the outcomes of multi-criteria decision problems [2]. Thus, it is widely acknowledged that the rankings of alternatives will vary among experts due to both the different evaluation criteria adopted and the subjective weights assigned to them by the experts. As a result, DMs will observe biases in the evaluations provided by the experts and variations in the degree of informativeness of such evaluations.

The decision support system (DSS) literature generally assumes that once the main opinions of the experts are presented to the DM, he will either utilize them [3] or ignore them [4]. Moreover, the DSS literature attempts to infer the preferences of the experts and maximize consensus when studying the rankings that are based upon subjective preferences [5,6]. In this setting, experts will provide judgments based on both their personal preferences and the information subsets (subjectively) chosen to assign their evaluations.

We move beyond the standard DSS setting and consider the formation of expectations by DMs and their capacity to extrapolate additional observations when presented with the evaluations of several alternatives by various experts. We must, therefore, consider two main sources

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http://dx.doi.org/10.1016/j.dss.2015.04.001
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of uncertainty: first, the uncertainty arising from the selection criteria and experts' subjective initial evaluations; and, second, the uncertainty due to the DM making additional observations.

Extensive literature studies DMs forecasting abilities when faced with a limited amount of *objective* information (see [7] for a comprehensive review). In this line of research, past observations by the DMs are essential for developing the forecasting process [8]. We will focus on the informativeness and the relative entropy of the evaluations. Both of these properties may reflect biases due to opinion similarities among the experts [9, 10], subjective weights assigned to the evaluations [11,12], or frictions in the aggregation process of the evaluations [13,14].

Our model exploits the biases of the experts observed in the dispersion and symmetry of the evaluations as well as the entropy associated with them. This latter measure of informativeness will be used to validate both the extrapolation of additional evaluations (allowing us to determine the stopping rule of the evaluation-generating process) and the subjective dispersion of the set of potential realizations considered by the DMs.

Following the DSS literature [15], we assume the DMs to expect ranking disagreements among the experts, despite the fact that the experts' subjective evaluations should all be equally reliable. As a result, DMs should try to infer a particular pattern in the evaluations to generate a ranking potentially more reliable than the one provided by the experts.

The main contribution of the ranking evaluation and validation method proposed in this paper is that it provides a quantifiable alternative to existing approaches relying on an objective distribution of the experts' evaluations.

Indeed, several methods already exist, such as PERT [16], designed to generate limit distributions, even when dealing with large degrees of data subjectivity. However, these Monte Carlo-based methods require a given probability distribution to define the data-generating process [17]. Thus, even if the information is based on a given density function, the subjectivity of the subset of data chosen and their weights would distort the process of obtaining a reliable limit distribution.

To support our analysis, we will perform a battery of Monte Carlo simulations and provide several alternative extrapolation approaches. The different rankings obtained will be compared with those resulting from the newly proposed framework.

Several attempts to deal with the subjectivity of the evaluation process and objectivize indexes generated through a common weighting criterion are also present in the empirical social science literature [18]. Nevertheless, economists expect a certain degree of subjectivity in the evaluations, which is considered to be optimal if each expert uses an empirically valid model [19]. As a result, economists concentrate on identifying and strategically selecting the expert whose preferences are closer to those of the DM [20–22]. The results obtained in this paper are, therefore, applicable to these branches, along with the general DSS literature.

The main contributions of the paper can be summarized as follows:

- We present a novel approach that allows DMs to assess the informativeness and reliability of a ranking based on the distributional bias of the evaluations received from the experts and their entropy.
- We illustrate how the distributional bias generated by the evaluations can be used to define a dynamic algorithm that allows DMs to extrapolate additional expected evaluations and modify the initial ranking proposed by the experts.
- We show that the entropy generated by the evaluations can be used to validate the reliability of the rankings extrapolated by the DMs and determine the stopping rule for the evaluation-generating algorithm.

We use a numerical example to demonstrate the applicability of the proposed framework. This example extends the analysis performed by [23] on the North Atlantic Treaty Organization (NATO) enlargement process.

The paper proceeds as follows. Section 2 introduces the basic geometric evaluation environment. Section 3 defines the first loop within the extrapolation process of the DMs. Section 4 describes the dynamic structure that allows the DMs to extrapolate further evaluations. Section 5 provides a numerical example with a ranking validation criterion based on the entropy generated by the evaluations. Section 6 concludes.

2. Geometric environment: defining expected evaluations

Consider a standard Euclidean plane. Let a value on the horizontal axis represent the opportunity score achieved by a given alternative and a value on the vertical axis represent the value of the threats (or threat level) posed by the alternative (see [24,25]). This setting is represented in Fig. 1a and b. Throughout the paper, both the evaluation of the opportunity score and that of the threat level of an alternative will be normalized. Thus, we will actually work in the Euclidean square $[0,1]^2 = [0,1] \times [0,1]$. In particular, at the point (1,0), opportunities are maximized and threats minimized; thus (1,0) can be referred to as the optimal reference point.

Let G be a group of experts assigning evaluations to a given set of alternatives. Let A_i stand for the i -th alternative being evaluated. Moreover, for every i, let

- x_i and y_i be the generic value that can be assigned to the alternative A_i as opportunity score (the x-variable) and threat level (the y-variable), respectively;
- x_i^m and x_i^M be the lowest and highest evaluations provided by G for the opportunity score of A_i;
- y_i^m and y_i^M be the lowest and highest evaluations provided by G for the threat level of A_i;
- $\bar{x}_i$ and $\bar{y}_i$ be the averaged values of the opportunity scores and threat levels assigned by G to A_i;
- $(\bar{x}_i, \ \bar{y}_i)$ be the initial position assigned by the DM to A_i after receiving the evaluations from G;
- $[x_i^m, \ x_i^M]$ and $[y_i^m, y_i^M]$ be the initial reference intervals considered by the DM for A_i;
- $[m, M]^2 = [x_i^m, x_i^M] \times [y_i^m, y_i^M]$ be the initial-evaluation-constrained domain;
- C_i be the circumference centered at (1,0) and passing through the point $(\bar{x}_i, \bar{y}_i)$;
- r_i be the radius of the circumference C_i, that is, $r_i = \sqrt{(\bar{x}_i - 1)^2 + (\bar{y}_i - 0)^2}$.

Fig. 1a and b illustrate the initial position $(\bar{x}_i, \bar{y}_i)$ assigned by the DM to the alternative A_i, the set of all points that represent potential improvements of $(\bar{x}_i, \bar{y}_i)$; that is, $\{(x, y) \in [0, 1]^2 : (x-1)^2 + (y-0)^2 \le r_i^2\}$, and the restriction of this set to the initial reference intervals; that is, $\{(x, y) \in [m, M]^2 : (x-1)^2 + (y-0)^2 \le r_i^2\}$. Also note that $(\bar{x}_i, \bar{y}_i)$ determines a division of $[0,1]^2$ and $[m, M]^2$ in four quadrants.

Throughout the evaluation process, we assume the DM to assign subjective probabilities to the set of potential realizations of both opportunity scores and threat levels for each alternative under analysis. Probabilities are updated as new information is received. In particular, we consider two subsequent phases.

- *Initial subjective probabilities*: We assume that the DM assigns initially, i.e., before receiving any evaluation, the same uniform density to each opportunity and threat scores defined in $[0,1]^2$. That is, the value of the density function at each potential opportunity and threat realization is initially equal to one. In other words, the DM faces complete uncertainty regarding the potential realizations of the evaluations before any information is provided.
- *Updated subjective probabilities*: We assume that after receiving the experts' evaluations, the DM subjectively assesses potential opportunity and threat realizations for each alternative on the base of the dispersion of the evaluations received.

To allow for a formalization of the second phase, which will consist of two loops, we need to introduce further notations and concepts.

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