"GROUP DECISION SUPPORT SYSTEMS IMPLEMENT BAYESIAN RATIONALITY"

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GROUP DECISION SUPPORT SYSTEMS

IMPLEMENT BAYESIAN RATIONALITY

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Abstract

When saying that group decisions are good, one often means that they are "externally Bayesian". Proposed by Madansky (1964), the externally Bayesian criterion requires that the decisions of the group look as if they were chosen by a Bayesian individual. A process due to DeGroot (1974) satisfies this criterion. We argue that this process corresponds to a group decision support system. This reinforces the claim that group decision support systems can improve group decision making.

Keywords: Bayes theory, common knowledge, decision support systems, group decision making.

1. Introduction

> Group decision support systems "are technologies designed to help people make faster, more satisfying, and ultimately "better" decisions than they may be making without them."
>
> [Jelassi and Beauclair (1987)]

Group decision support systems (GDSS) are often said to help groups of people take better decisions. They constitute, however, an expensive technology. Therefore, their desirability in particular circumstances with specific decision making criteria needs to be examined carefully.

Consider for instance the situation where the members of a group agree on a utility function, but have different opinions concerning the prior distribution of a relevant unknown state of nature. In this context, Madansky (1964) stipulates that the group should be externally Bayesian:

> any sequence of group decisions, he says, can be come to by some individual who is a Bayesian, who starts with a particular prior density, and who observes the sequence of x's observed by the group.

Can a group decision support system help fulfill this requirement?

An affirmative answer to this question is developed below. We argue that a GDSS is indeed sufficient for implementing Bayesian rationality.

The externally Bayesian criterion is formally stated and discussed in the next section. In the third section, we present a procedure, due to DeGroot (1974), which makes a group externally Bayesian. This procedure builds up a group consensus through anonymous communication among group members. We point out that it corresponds in practice to a group decision support system. Further research directions are sketched in our fourth and last section.

2. The externally Bayesian criterion

Consider a group with members labeled $i = 1,\ldots,n$. All group members agree that the common utility $u(a,\theta)$ results from choosing action a from the set $\mathbf{A}$, when θ is the realised, a priori unknown, state of nature. Let θ belong to a given possibility set Θ. In period 0, each expert of the group has a personal opinion about θ that can be represented by a distribution function F_{i0}, of density $p_{i0}(\theta)$, on Θ. [3]

Figure 1 below illustrates now the timing of group decisions. An action is selected from $\mathbf{A}$ in period 0; a new action is chosen in period 1, after a signal x about θ is observed. All experts agree on the likelihood of x given θ, denoted $f(x|\theta)$. Suppose also that each one is a Bayesian. Hence, at time $t = 0,1$ member i will recommend an action that maximises her

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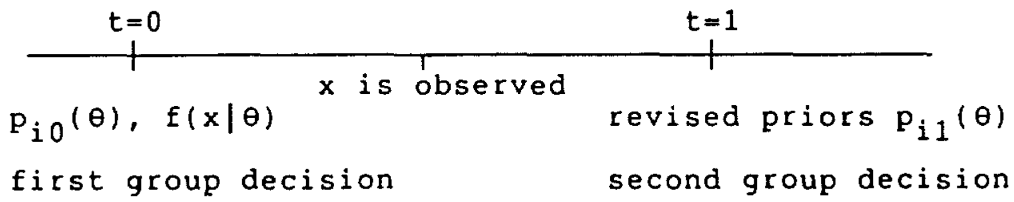
[3] Formally, Θ is a totally ordered measure space with σ-field Σ and measure $m:\Sigma \longrightarrow [0,\infty)$; each $p_{it}(\cdot)$, $t = 0,1$ and $i = 1,\ldots,n$, is the density with respect to m of the distribution function $F_{it}:\Theta \longrightarrow [0,1]$.



<u>figure 1</u>: timing of group decisions

expected utility [4]

$$\mathbf{P}_{it}\, u(a,\theta) = \int u(a,\theta) p_{it}(\theta)\; dm(\theta)$$

where $p_{i1}(\theta)$ is the new prior probability of θ, obtained from $p_{i0}(\theta)$ via Bayes' formula:

$$p_{i1}(\theta) = \frac{f(x|\theta)\; p_{i0}(\theta)}{\int f(x|\theta) p_{i0}(\theta)\; dm(\theta)} \quad .$$

Assume now that, based on its members' opinions, the group has chosen action a_0 in period 0, and switched to a_1 in period 1 after x was observed. The group is called <u>externally Bayesian</u> if there exists a pair of group prior densities $\pi_0(\theta)$, $\pi_1(\theta)$ on θ for which a_0 maximises the group expected utility

$$\mathbf{P}_0\, u(a,\theta) = \int u(a,0)\pi_0(\theta)\; dm(\theta),$$

and a_1 maximises

[4] To make sure this optimal action exists, one may assume that $\mathbf{A}$ is a compact set and $\mathbf{P}_{it}u(\cdot,\theta)$ is continuous on $\mathbf{A}$ for each θ and t = 1,2.

$$P_1\ u(a,\theta) = \int u(a,\theta)\pi_1(\theta)\ dm(\theta)$$

with $\pi_1(\theta)$ being a Bayesian update of $\pi_0(\theta)$, that is

$$\pi_1(\theta) = \frac{f(x|\theta)\ \pi_0(\theta)}{\int f(x|\theta)\pi_0(\theta)\ dm(\theta)} .$$

The externally Bayesian criterion specifies a structure on the sequence of group decisions, that rules out many intuitive ways to aggregate the experts' advice. One such intuitive but unsatisfactory procedure is the "opinion pool" proposed by Stone (1961). This procedure builds up group prior densities by taking a given linear weighted average of the specialists' subjective densities; i.e.

(1) $$\pi_t(\theta) = w_1 p_{1t}(\theta) + \ldots + w_n p_{nt}(\theta)$$

for $t = 0,1$ and $w_1,\ldots,w_n$ nonnegative summing up to 1. Madansky (1964) shows that a group using this method is not externally Bayesian, unless one of the w_i's is unity so that the group is practically lead by a dictator. The reason is that the weights w_i's are fixed over time. As it will now be proven, a better procedure is obtained when the weights are adjusted according to the experts' relative reputations.

Interpret the weight w_{it} as the probability that expert i's forecast at time t is the most accurate. In period 0, individual i's prediction about signal x is summarized by the density

$$(2) \qquad f_i(x) = \int f(x|\theta)p_{i0}(\theta)\ dm(\theta).$$

At time 1, it now seems reasonable to update the initial weight, denoted $w_i^{\,0}$, so that more importance is given to expert i's opinion if her forecast about x was good. The new weight $w_i^{\,1}$ is then computed using Bayes' formula:

$$(3) \qquad w_i^{\,1} = \frac{w_i^{\,0} f_i(x)}{w_1^{\,0} f_1(x) + \ldots + w_n^{\,0} f_n(x)} .$$

This is indeed an adequate method, as the following result shows.

<u>Lemma 1</u>: (Madansky (1964)) A group is externally Bayesian when it takes as its prior distribution a linear weighted average of its members' subjective distributions, the weights being updated through formulae (2)-(3).

PROOF:

The group prior density in period 1 is now given by

$$\pi_1(\theta) = w_1^{\,1} p_{11}(\theta) + \ldots + w_n^{\,1} p_{n1}(\theta)$$

$$= \frac{\sum_{i=1}^{n} w_i^{\,0}\ f_i(x)\ p_{i1}(\theta)}{\sum_{j=1}^{n} w_j^{\,0} \int f(x|\theta)\ p_{j0}(\theta)\ dm(\theta)}$$

$$= \frac{\sum_{i=1}^{n} w_i^{\,0}\ f(x|\theta)\ p_{i0}(\theta)}{\int f(x|\theta) \sum_{j=1}^{n} w_j^{\,0}\ p_{j0}(\theta)\ dm(\theta)}$$

$$= \frac{f(x|\theta)\ \pi_0(\theta)}{\int f(x|\theta)\ \pi_0(\theta)\ dm(\theta)}$$

The last expression means that the group prior density is updated using Bayes' formula. Hence, the group is externally Bayesian. ▒

The above result is interesting because it suggests valuable alternatives to dictatorship in group decision making. Dictatorship cannot be rejected for ethical reasons here, since experts' judgments, not individual preferences, are being considered. The prevalence of one's prior probability distribution must be based on her knowledge of the state of nature, and matters of knowledge, unlike matters of taste, imply that some persons are more expert than others. It is, however, unusual that one's expertise is always overwhelming. There are many cases in group decision making where people have equivalent expertise but still distinct opinions. Then it seems better to enhance communication between members so that a consensus on the probability assessments is reached. Such a philosophy underlies the group decision support systems presented in the next section.

3. A procedure for reaching a consensus over group priors

The problem of how to get a consensus among the members of a group has drawn much research recently. The new interest arose primarily from Aumann (1976)'s formalization of the notion of common knowledge.[5] Intuitively, an event is common knowledge among the members of a group if each one knows it, each one knows that everybody knows it, each one knows that everybody knows that everybody knows it, and so on... Aumann shows that if two forecasters have the same prior, if their respective cognitive schemes are represented by partitions of Θ, and if their posteriors (or updated priors) are common knowledge, then these posteriors must be equal, even when each individual gets different private information. Thereafter, assuming that each one of two experts knows the information the other might have obtained, i.e. each expert knows her fellow's partition of Θ, supposing also that the partitions are finite, Geanakoplos and Polemarchakis (1982) designed a process where the two experts finally agree on a posterior distribution after communicating to each other their successive revisions of the prior.

The theory of common knowledge presupposes that the group members have an identical prior and receive different private information. We consider here the symmetric case where individuals have different prior beliefs while they get the same signal. In this context, DeGroot (1974) constructed a procedure that leads to a group prior distribution over which all members agree. This procedure is described and analysed below.

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[5] Milgrom (1981) gives an axiomatic characterisation of common knowledge.

Procedure

Initially, in period $t = 0$, each expert has an opinion about θ that is represented by a density function $p_{i0}^{0}(\theta)$.

First, each expert makes public her subjective density.

Second, when all subjective densities are common knowledge, each expert revises her opinion. Supposedly, the new subjective densities are linear weighted averages of the revealed densities. To describe this process in formal terms, denote expert i's announced subjective density by $p_{i0}^{k}(\cdot)$, and assume that she concedes a positive weight v_{ij} to each group member's opinion; once she knows her colleagues' densities, she adopts the new subjective density

(4) $$p_{i0}^{k+1}(\theta) = v_{i1}p_{10}^{k}(\theta) + \ldots + v_{in}p_{n0}^{k}(\theta).$$

Third, one goes back to the first step, with $p_{i0}^{k+1}(\cdot)$ as expert i's subjective density. The communication/revision process is repeated again and again, until the personal densities do not sensibly vary any more.

Convergence of the procedure to an agreed-upon density function is insured by the following result:

Lemma 2: (DeGroot (1974)) Using the above procedure, group members end up giving implicitly the same weights $u_1,\ldots,u_n$ to each other's opinion. Hence, and agreed-upon density $\mu_0(\theta)$ emerges that is in fact

(5) $$\mu_0(\theta) \equiv u_1p_{10}(\theta) +\ldots+ u_np_{n0}(\theta).$$

PROOF:

Let us put the weights v_{ij} together into a matrix $V \equiv (v_{ij})$. At the second iteration of the procedure, formula (4) can be written as

$$
\begin{aligned}
p_{i0}^{2}(\theta) &= v_{i1}p_{10}^{1}(\theta) + \dots + v_{in}p_{n0}^{1}(\theta) \\
&= v_{i1}[v_{11}p_{10}^{0}(\theta) + \dots + v_{1n}p_{n0}^{0}(\theta)] + \dots \\
&\qquad + v_{in}[v_{n1}p_{10}^{0}(\theta) + \dots + v_{nn}p_{n0}^{0}(\theta)] \\
&= [v_{i1}v_{11} + \dots + v_{in}v_{n1}]\cdot p_{10}^{0}(\theta) + \dots \\
&\qquad + [v_{i1}v_{1n} + \dots + v_{in}v_{nn}]\cdot p_{n0}^{0}(\theta) \\
&\equiv \sum_{j=1}^{n} w_{ij}^{(2)}\, p_{j0}(\theta)\ ,
\end{aligned}
$$

where the $w_{ij}^{(2)}$'s, $w_{ij}^{(2)} \equiv [v_{i1}v_{1j} + \dots + v_{in}v_{nj}]$, are just the terms of the matrix $V^2 = V\cdot V$. Hence, by a trivial induction, one can say that, at the kth iteration of the procedure, each group member i values his colleagues' opinions according to subjective weights that appear in row i of the matrix V^k.

The first assertion of the lemma – the appearance of common weights $u_1,\dots,u_n$ – can now be established using the theory of Markov chains. The matrix V is a stochastic matrix with positive entries. Thus, by theorem 2.1 of Çinlar (1975), there must exist a unique vector of weights $\mathbf{u} \equiv (u_1,\dots,u_n)$ such that for all i: $\lim_{k\to\infty} w_{ij}^{(k)} = u_j$

or equivalently, $\mathbf{u}\cdot V = \mathbf{u}$.

The emergence of an agreed-upon group density is now at hand since

$$\text{for all } i: \quad \lim_{k\to\infty} p_{i0}^{\,k}(\theta) = \lim_{k\to\infty} \sum_{j=1}^{n} w_{ij}^{(k)} p_{i0}(\theta)$$

$$= \sum_{j=1}^{n} u_j \, p_{j0}(\theta)$$

$$= \mu_0(\theta). \qquad \blacksquare$$

Implementing the above procedure requires in general a group decision support system. To display all opinions to everybody, a large common viewing screen is necessary. To suppress pressure coming from shyness, low status, power struggle or controversial ideas, devices that allow anonymous inputs are essential. To make information circulate efficiently among group members, electronic messaging can help. Finally, to behave as a Bayesian, to compute and update densities, each group member may need a computer terminal with decision-theoretic aids.

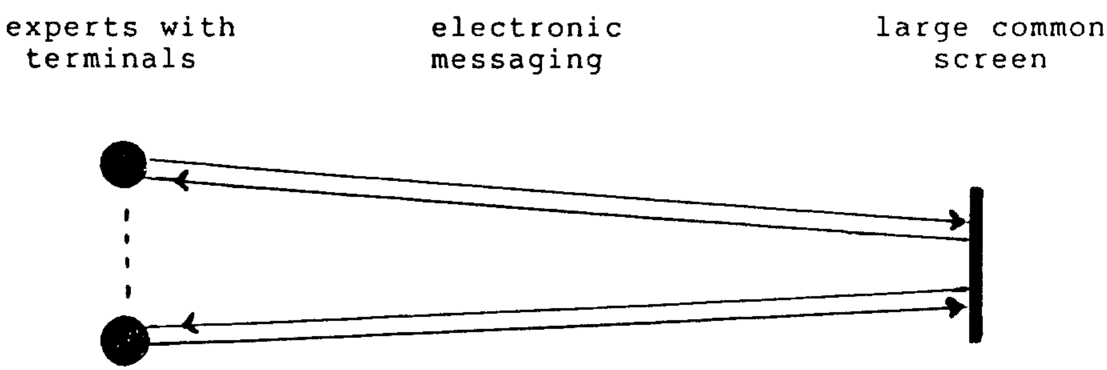

figure 2: a GDSS that iteratively elicits an agreed-upon prior density

Actually, at least two particular GDSS can be imagined.

One is suggested by the procedure itself. It would elicit the subjective densities, make them public, let the individuals revise their opinion, elicit the new subjective densities, make them public, and so on, until a consensus is reached. This GDSS is illustrated in figure 2. Another GDSS is suggested by the proof of lemma 2 and is described in figure 3. It would elicit the subjective weights v_{ij} and the subjective densities $p_{i0}(\theta)$, calculate the vector $\mathbf{u} = (u_1,\ldots,u_n)$, compute the agreed-upon prior distribution through formula (5), and then announce it.

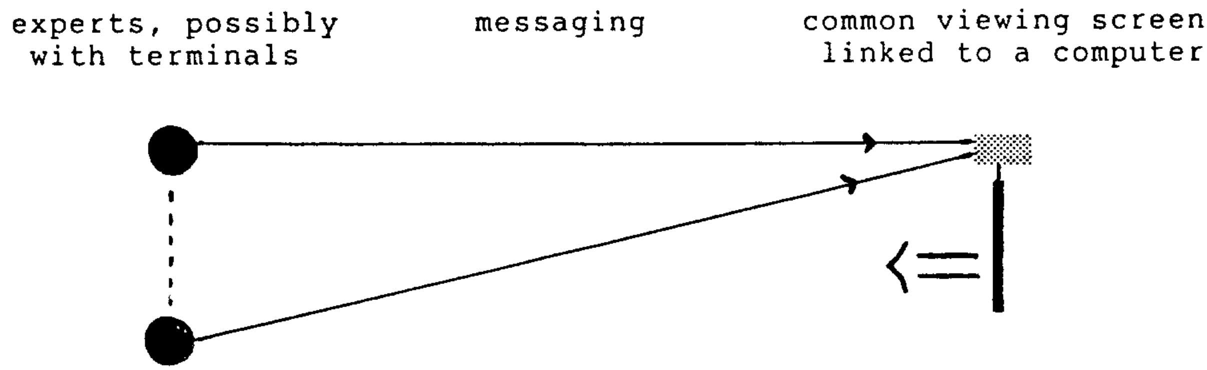

figure 3: a GDSS that computes an agreed-upon prior density after a one-shot elicititation round

The main benefit of using these group decision support systems is stated in the following result.

Theorem 1: Suppose all group members are Bayesians. The group is externally Bayesian if it uses one of the above decision support systems before taking a decision at time 0.

PROOF:

By lemma 2, if the group uses one of the above GDSS, it reaches a consensus over a prior density distribution. Let this agreed-upon density at time 0 be $\mu_0(\theta)$. Then each expert and the group itself have the same expected utility

$$P_0\ u(a,\theta) = \int u(a,0)\mu_0(\theta)\ dm(\theta).$$

Since group members are Bayesians, everyone will recommend an action that maximises this expected utility, so the group will take such an action, say a_0.

At time 1, each Bayesian group member will have the same updated prior distribution

$$\mu_1(\theta) = \frac{f(x|\theta)\ \mu_0(\theta)}{\int f(x|\theta)\mu_0(\theta)\ dm(\theta)}.$$

Hence the group will adopt this prior, and it will then again choose an action, say a_1, that maximises the expected utility

$$P_1\ u(a,\theta) = \int u(a,\theta)\mu_1(\theta)\ dm(\theta).$$

A group behaving in such a fashion is externally Bayesian. $\blacksquare$

Although they are theoretically equivalent, the two previous GDSS may perform quite differently in practice. Careful experimentation would help clarifying this matter. It might happen, for instance, that several group members would be puzzled by a GDSS, like the one **depicted in figure** 3, which elicits their personal opinion and comes out with some density distribution. These individuals would perhaps fear that the group decision process gets out of hand. They could then ask for the GDSS to be restarted after x is observed, so that they could input their revised beliefs. If this is done, however, it is interesting to note that the group can still be externally Bayesian.

<u>Theorem 2</u>: Suppose all group members are Bayesians. The group can be externally Bayesian when its priors at time 0 and 1 are generated through the group decision support system depicted in figure 3.

PROOF:

Let the v_{ij}^0's be the experts' subjective weights at time 0. Also let $u_1^0, \ldots, u_n^0$ be the agreed-upon vector of weights in period 0. By definition of the GDSS and the theory of Markov chains (Çinlar (1975): theorem 2.1, p. 152), the u_i^0's are the unique solution to the equations

$$(6) \qquad u_j^0 = \sum_{i=1}^{n} u_i^0 \, v_{ij}^0 \; , \qquad \sum_{i=1}^{n} u_i^0 = 1 \; ,$$

Each expert being a Bayesian, all subjective weights at time 1, denoted v_{ij}^1, must be obtained from the subjective weights at time 0 through Bayes formula, i.e.

$$v_{ij}^1 = \frac{v_{ij}^0 \; f_j(x)}{v_{i1}^0 f_1(x) + \ldots + v_{in}^0 f_n(x)}$$

Let the GDSS at time 1 simply rescale these subjective weights so that it considers v_{ij}^1 to be equal to $v_{ij}^0(f_j(x)/f_i(x))$. Then the

GDSS must compute a vector of agreed-upon weights $u_1^1, \ldots, u_n^1$ that satisfy the equations

$$u_j^1 = \sum_{i=1}^{n} u_i^1 \, v_{ij}^1 ,$$

$$= \sum_{i=1}^{n} u_i^1 \, v_{ij}^0 (f_j(x)/f_i(x)) .$$

Thanks to (6), a solution to this system is precisely

$$u_i^1 = u_i^0 \, f_i(x) .$$

A rescaling of these weights so that they sum up to 1 yields

$$u_i^1 = \frac{u_i^0 \, f_i(x)}{u_1^0 f_1(x) + \ldots + u_n^0 f_n(x)} .$$

By lemma 1, the group is then externally Bayesian. ▒

5. Conclusion

Several authors have recently pointed out that "there is little conclusive knowledge regarding how structure can be added to a group decision process to yield better decision making." (DeSanctis and Gallupe (1987), p. 595) Our present paper provides a partial reply to this statement. We describe two group decision support systems and we show how they can make group decisions achieve Bayesian rationality in particular contexts.

We made however, several simplistic assumptions. Fo.

instance, in the procedure yielding a consensus, we assumed away that a member could change her subjective weights once she hears her colleagues' opinion. But "at different points in time, the group is likely to interpret comments differently, use decision rules differently, or rely on power in different ways." (DeSanctis and Gallupe (1987), p. 592) To deal with such features requires further research.

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