Optimization of threshold memberships over fuzzy decision process

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1 Introduction

Since Bellman and Zadeh has proposed three – deterministic, stochastic and fuzzy – systems on multistage decision processes in fuzzy environment [4, §4,5], an intensive study on fuzzy decision making under uncertainty has been developed both in theory and in its wide applications ([1, 5, 15] and others). In Markov decision processes [6, 17], it has been tacitly known that there exists an optimal policy which is Markov for the additive criterion, where Markov policy takes decision on the basis of only today’s state. Recently, from a stochastic control theory, Iwamoto has developed Bellman and Zadeh’s fuzzy decision-making on the stochastic system for a non-additive (minimum) criterion. He has shown that an optimal policy does not exist in Markov class for minimum criterion but does exist in general class, where general policy depends on state-sequence up until today [7, 8, 9, 10, 11, 12, 13, 14, 18]. His tool is identical twins – both dynamic programming [2] and invariant imbedding [3, 16] – for non-additive criterion in stochastic system [8, 9].

In this paper, we consider a “threshold probability” decision-making in fuzzy environment. On the multi-stage stochastic control process, we evaluate the threshold probability that the minimum criterion exceeds a lower membership-degree. The minimum criterion denotes a total membership function of the multistage fuzzy decision process with stage-wise membership functions and a goal membership function. It is the membership function of intersection of the underlying fuzzy sets [4, p.144, §4,5]. Under the controlled Markov chain we optimize the threshold probability not in general class but in Markov class. We show that this choice will be successful; there exists an optimal policy in Markov class. We also derive the recursive relation for the threshold probability. We use the notations and terminology in [4, 8, 9].

2 Decision Process with Threshold Probability

Let us consider an $N$-stage ($N \geq 2$) stochastic decision process $\{(X_n, U_n)\}_{0}^{N}$ on a finite state space $X$ and decision space $U$, which is governed by a Markov transition law $p = \{p(\cdot|\cdot, \cdot)\}$:

$$p(y|x, u) \geq 0, \quad \sum_{y \in X} p(y|x, u) = 1.$$  

Thus $p(y|x, u)$ is a conditional probability that the next state $X_{n+1}$ will be $y$ when the current state $X_n$ is $x$ and current decision $U_n$ is $u$:

$$P(X_{n+1} = y | X_n = x, U_n = u) = p(y|x, u).$$

This transition is expressed as $X_{n+1} \sim p(\cdot | x, u)$.
We begin to introduce a large class of policies, which depend not only on today's state but also on state-to-date. Let $X^n := X \times X \times \cdots \times X$ be direct product of $n$ state spaces $X$. A mapping $\sigma_n : X^{n+1} \to U$ is called $n$-th general decision function, whose sequence $\sigma = \{\sigma_0, \sigma_1, \ldots, \sigma_{N-1}\}$ constitutes a general policy. The set of all general policies $\Pi_g$ is called general class. When each general decision function $\sigma_n$ depends only on the last (= current) state, the general policy reduces to a Markov policy $\pi = \{\pi_0, \pi_1, \ldots, \pi_{N-1}\}$. Let Markov class $\Pi$ denote the set of all Markov policies. Thus we have an inclusion relation: $\Pi \subset \Pi_g$.

Further, given an $n$-th membership function $\mu_n : X \times U \to [0, 1]$, and a goal membership function $\mu_G : X \to [0, 1]$, we can introduce the membership function, $\Pi \subset \Pi_g$. This choice will be turned to generate a valid recursive equation. Any Markov policy $\pi(\in \Pi)$ determines the threshold probability in $P(x_0)$, which is a "partial" multiple sum:

$$\begin{align*}
\text{Maximize} & \quad P_{x_0}^{\pi}(\mu_0 \wedge \mu_1 \wedge \cdots \wedge \mu_{N-1} \wedge \mu_G \geq \alpha) \\
\text{subject to} & \quad (i)_n X_{n+1} = p(\cdot | x_n, u_n) \\
& \quad (ii)_n u_n \in U \quad 0 \leq n \leq N-1
\end{align*}$$

where $P_{x_0}^{\pi}$ is the (discrete) probability measure on the history space $H_N := X \times U \times X \times U \times \cdots \times U \times X$ $(2N+1)$-factors induced through an initial state $x_0$, the Markov transition law $p$ and a Markov policy $\pi(\in \Pi)$.

We dare to maximize the threshold probability over Markov class $\Pi$. We do not optimize it over general class $\Pi_g$. This choice will be turned to generate a valid recursive equation. Any Markov policy $\pi(\in \Pi)$ determines the threshold probability in $P(x_0)$, which is a "partial" multiple sum:

$$P_{x_0}^{\pi}(\mu_0 \wedge \mu_1 \wedge \cdots \wedge \mu_{N-1} \wedge \mu_G \geq \alpha) = \sum_{(x_1, x_2, \ldots, x_N) \in (*)} \sum \cdots \sum p_0 p_1 \cdots p_{N-1}$$

where the domain $(*)$ is the set of all $(x_1, x_2, \ldots, x_N) \in X^N$ satisfying

$$\mu_0(x_0, u_0) \wedge \mu_1(x_1, u_1) \wedge \cdots \wedge \mu_{N-1}(x_{N-1}, u_{N-1}) \wedge \mu_G(x_N) \geq \alpha.$$  

Here the sequence of decisions $\{u_0, u_1, \ldots, u_{N-1}\}$ in (1),(2) is uniquely determined through Markov policy $\pi = \{\pi_0, \ldots, \pi_{N-1}\}$:

$$u_0 = \pi_0(x_0), \quad u_1 = \pi_1(x_1), \quad \ldots, \quad u_{N-1} = \pi_{N-1}(x_{N-1}).$$

As for controlling threshold probability on the Markov chain $\{(X_n, U_n)\}$ with reward functions $\{r_n\}_{0}^{N-1}$ and a lower level value $c$, Markov class $\Pi$ is not enough for additive criteria:

$$Q_0(x_0) \quad \text{Maximize} \quad P_{x_0}^{\pi}(r_0 + r_1 + \cdots + r_{N-1} + r_N \geq c)$$

subject to $\quad (i)_n, (ii)_n \quad 0 \leq n \leq N-1$

but general class $\Pi_g$ is enough [8, 18]. However, in this paper, we dare to maximize the threshold probability for minimum criteria over Markov class.

Thus our problem $P_0(x_0)$ is to find the maximum value function $v_0 = v_0(x_0)$ and an optimal policy $\pi^*(\in \Pi)$ which attains the maximum:

$$v_0(x_0) = P_{x_0}^{\pi^*}(\mu_0 \wedge \cdots \wedge \mu_{N-1} \wedge \mu_G \geq \alpha) \quad x_0 \in X$$

$$= \max_{\pi \in \Pi} P_{x_0}^{\pi}(\mu_0 \wedge \cdots \wedge \mu_{N-1} \wedge \mu_G \geq \alpha).$$
3 Recursive formula

We consider the subproblem starting at state $x_n(\in X)$ on $n$-th stage and terminating on the final $N$-th stage ($0 \leq n \leq N-1$):

$$P_n(x_n) \quad \text{Max} \quad P_{x_n}^\pi(\mu_n \land \cdots \land \mu_{N-1} \land \mu_G \geq \alpha) \quad \text{s.t.} \quad (i)_m, (ii)_m \quad n \leq m \leq N-1$$

where $\pi = \{\pi_n, \ldots, \pi_{N-1}\}$ is taken over Markov class from $n$-th stage on $\Pi(n)$.

Let $v_n(x_n)$ be the maximum value, where

$$v_N(x_N) \triangleq P(\mu_G \geq \alpha \mid X_N = x_N) = \begin{cases} 1 & x_N \geq \alpha \\ 0 & \text{otherwise} \end{cases} \quad x_N \in X. \quad (5)$$

Lemma 3.1 We have for any $0 \leq n \leq N-1$, $x_n \in X$ and $\pi = \{\pi_n, \ldots, \pi_{N-1}\} \in \Pi(n)$

$$P_{x_n}^\pi(\mu_n \land \cdots \land \mu_G \geq c) = \begin{cases} \sum_{x_{n+1} \in X} P_{x_{n+1}}^\pi(\mu_{n+1} \land \cdots \land \mu_G \geq c)p(x_{n+1} \mid x_n, u_n) & \text{if} \quad \mu_n(x_n, u_n) \geq \alpha \\ 0 & \text{otherwise} \end{cases}$$

where $u_n = \pi_n(x_n)$, $\pi' = \{\pi_{n+1}, \ldots, \pi_{N-1}\}$ and $P_{x_n}^{\pi'} := P$ in (5) for $\pi = \{\pi_{N-1}\}$.

Equivalently, in terms of multiple sum, we get

$$\sum \sum \cdots \sum p_{n+1}p_{n+2} \cdots p_N = \begin{cases} \sum_{x_{n+1} \in X} \left[ \sum \sum \cdots \sum p_{n+2} \cdots p_N \right] p(x_{n+1} \mid x_n, u_n) & \text{if} \quad \mu_n(x_n, u_n) \geq \alpha \\ 0 & \text{otherwise} \end{cases}$$

where $p_m = p(x_m \mid x_{m-1}, u_{m-1})$, $u_m = \pi_m(x_m)$, $(*)$ denotes the partial multiple sum over $(x_{n+1}, \ldots, x_N) \in X \times \cdots \times X$ satisfying $\mu_n(x_n, u_n) \land \cdots \land \mu_G(x_N) \geq \alpha$, and $(\ast)$ denotes $(x_{n+2}, \ldots, x_N)$ satisfying $\mu_{n+1}(x_{n+1}, u_{n+1}) \land \cdots \land \mu_G(x_N) \geq \alpha$.

Thus we have the backward recursive relation:

**Theorem 3.1 (Recursive Equation)**

$$v_N(x) = \begin{cases} 1 & \text{if} \quad \mu_G(x) \geq \alpha \\ 0 & \text{otherwise} \end{cases} \quad x \in X$$

$$v_n(x) = \begin{cases} \text{Max}_{u;\mu_n(x,u) \geq c} \sum_{y \in X} v_{n+1}(y)p(y \mid x, u) & \text{if} \quad \exists u \; ; \; \mu_n(x,u) \geq \alpha \\ 0 & \text{otherwise} \end{cases} \quad x \in X, \quad 0 \leq n \leq N-1. \quad (6)$$

Now let us take any pair $(n, x)$. If it satisfies $\mu_n(x,u) \geq \alpha$, then let $\pi_n^*(x)$ denote a $u^* \in U$ which attains the maximum in (6). Otherwise, let $\pi_n^*(x)$ denote any $u \in U$. Then we have an optimal $n$-th decision function $\pi_n^* : X \rightarrow U$. Thus we construct an optimal policy $\pi^* = \{\pi_0^*, \ldots, \pi_{N-1}^*\}$ in Markov class $\Pi$. 
4 Bellman and Zadeh’s Model

Let us consider maximizing the threshold probability with lower membership-degree $\alpha = 0.7$ on Bellman and Zadeh’s model [4, pp.B154]:

\[
\begin{align*}
\text{Max} & \quad P_{x_0}^{n} (\mu_0(U_0) \land \mu_1(U_1) \land \mu_G(X_2) \geq 0.7) \\
\text{s.t.} & \quad (i) \quad X_{n+1} \sim p(\cdot|x_n, u_n) \quad n = 0, 1 \\
& \quad \quad (ii) \quad u_n \in U
\end{align*}
\]

where the numerical data is theirs:

- $\mu_0(a_1) = 0.7$, $\mu_0(a_2) = 1.0$;
- $\mu_1(a_1) = 1.0$, $\mu_1(a_2) = 0.6$;
- $\mu_G(s_1) = 0.3$, $\mu_G(s_2) = 1.0$, $\mu_G(s_3) = 0.8$


| $P(x_{n+1}|x_n, a_1)$ | $P(x_{n+1}|x_n, a_2)$ |
|------------------------|------------------------|
| $x_n \backslash x_{n+1}$ | $s_1$ | $s_2$ | $s_3$ | $s_1$ | $s_2$ | $s_3$ |
| $s_1$ | 0.8 | 0.1 | 0.1 | 0.1 | 0.9 | 0.0 |
| $s_2$ | 0.0 | 0.1 | 0.9 | 0.8 | 0.1 | 0.1 |
| $s_3$ | 0.8 | 0.1 | 0.1 | 0.1 | 0.0 | 0.9 |

The backward recursion (6) yields optimal solution in Markov class II — a pair of a sequence of optimal value functions

\[ v_0 = v_0(x_0), \; v_1 = v_1(x_1), \; v_2 = v_2(x_2) \]

and an optimal policy

\[ \pi^* = \{\pi_0^*(x_0), \; \pi_1^*(x_1)\}. \]

The optimal solution is tabulated as

<table>
<thead>
<tr>
<th>$x_n$</th>
<th>$v_2(x_2)$</th>
<th>$v_1(x_1)$</th>
<th>$\pi_1^*(x_1)$</th>
<th>$v_0(x_0)$</th>
<th>$\pi_0^*(x_0)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$s_1$</td>
<td>0</td>
<td>0.2</td>
<td>$a_1$</td>
<td>0.92</td>
<td>$a_2$</td>
</tr>
<tr>
<td>$s_2$</td>
<td>1</td>
<td>1.0</td>
<td>$a_1$</td>
<td>0.28</td>
<td>$a_1, a_2$</td>
</tr>
<tr>
<td>$s_3$</td>
<td>1</td>
<td>0.2</td>
<td>$a_1$</td>
<td>0.28</td>
<td>$a_1$</td>
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</table>

Table 1: Optimal Solution

Furthermore, we have another two methods. One is stochastic decision tree-table methods(Figure 1). The other is total enumeration of all Markov policy and related threshold probability vector(Table 2).

So we have three approaches. Through these three approaches, we have obtained optimal solution; optimal value $\{0.92, 0.28, 0.28\}$ and optimal policy $\pi^*$. 
$w_0(s_1) = \max_{\pi \in \Pi} P_{\pi}^0(\mu_0(U_0) \land \mu_1(U_1) \land \mu_G(X_2) \geq 0.7)$

Figure 1: Two-stage stochastic decision tree-table from state $s_1$
\[ J(x_0; \pi) = P^x_{x_0} (\mu_0 \land \mu_1 \land \mu_G \geq 0.7) \]

Table 2: all threshold-probability vectors \( J(\pi) = \left( \frac{J(s_1; \pi)}{J(s_2; \pi)} \frac{J(s_3; \pi)}{} \right) \), where \( \pi = \{\pi_0, \pi_1\} \) is Ma

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</table>

| \( \pi_1 \) | \( a_1 \) | \( 0.28 \) | \( 0.26 \) | \( 0.26 \) | \( 0.18 \) | \( 0.16 \) | \( 0.12 \) | \( 0.1 \) | \( 0.02 \) |
| \( \pi_0 \) | \( a_1 \) | \( 0.28 \) | \( 0.1 \) | \( 0.18 \) | \( 0.0 \) | \( 0.28 \) | \( 0.1 \) | \( 0.18 \) | \( 0.0 \) |
| \( a_1 \) | \( 0.28 \) | \( 0.26 \) | \( 0.18 \) | \( 0.16 \) | \( 0.12 \) | \( 0.1 \) | \( 0.02 \) | \( 0.0 \) |
| \( a_1 \) | \( 0.28 \) | \( 0.1 \) | \( 0.18 \) | \( 0.0 \) | \( 0.28 \) | \( 0.1 \) | \( 0.18 \) | \( 0.0 \) |
| \( a_2 \) | \( 0.2 \) | \( 0.02 \) | \( 0.2 \) | \( 0.02 \) | \( 0.18 \) | \( 0.18 \) | \( 0.0 \) |
| \( a_2 \) | \( 0.28 \) | \( 0.26 \) | \( 0.18 \) | \( 0.16 \) | \( 0.12 \) | \( 0.1 \) | \( 0.02 \) | \( 0.0 \) |
| \( a_2 \) | \( 0.28 \) | \( 0.26 \) | \( 0.18 \) | \( 0.16 \) | \( 0.12 \) | \( 0.1 \) | \( 0.02 \) | \( 0.0 \) |
| \( a_2 \) | \( 0.28 \) | \( 0.26 \) | \( 0.18 \) | \( 0.16 \) | \( 0.12 \) | \( 0.1 \) | \( 0.02 \) | \( 0.0 \) |

| \( \pi_1 \) | \( a_2 \) | \( 0.92 \) | \( 0.92 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) |
| \( \pi_0 \) | \( a_1 \) | \( 0.28 \) | \( 0.1 \) | \( 0.18 \) | \( 0.0 \) | \( 0.28 \) | \( 0.1 \) | \( 0.18 \) | \( 0.0 \) |
| \( a_1 \) | \( 0.28 \) | \( 0.26 \) | \( 0.18 \) | \( 0.16 \) | \( 0.12 \) | \( 0.1 \) | \( 0.02 \) | \( 0.0 \) |
| \( a_2 \) | \( 0.92 \) | \( 0.92 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) |
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| \( a_2 \) | \( 0.28 \) | \( 0.26 \) | \( 0.18 \) | \( 0.16 \) | \( 0.12 \) | \( 0.1 \) | \( 0.02 \) | \( 0.0 \) |
| \( a_2 \) | \( 0.92 \) | \( 0.92 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) | \( 0.02 \) |
References


