

Problemset 3

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March 10, 2017

1 Inventory Control with Forecasts

1.1 Part (a)

In the standard news-vendor problem, the inventory manager has to minimise $G(Q)$ with the optimal Q^* when the random demand is D . With selling price per unit p , cost per unit c and salvage value per unit s , we define it as:

$$G(Q) = (p - c)\mathbb{E}[(D - Q)^+] + (c - s)\mathbb{E}[(Q - D)^+] = b\mathbb{E}[(D - Q)^+] + h\mathbb{E}[(Q - D)^+]$$

Following the discussion in class, the optimal inventory decision Q^* must satisfy $F(Q^*) = \frac{b}{b+h}$, where F is the demand distribution. However, in this problem, the demand distribution depends on the forecast $y \in \{l, s\}$. Hence, the manager will make his decision for the optimal policy based on y .

$$Q^*(y) = \begin{cases} F_l^{-1}\left(\frac{b}{b+h}\right) & \text{if } y = l \\ F_s^{-1}\left(\frac{b}{b+h}\right) & \text{if } y = s \end{cases}$$

Since the optimal decision of the manager depends on the accurate forecast of the probability distribution of the demand, this policy will be considered as a closed loop policy.

1.2 Part (b)

We use the given hint to state the dynamics of the problem.

$$x_{k+1} = x_k + u_k - w_k, \quad y_{k+1} = \xi_k$$

where ξ_k takes values L and S for large and small demand with probabilities q and $1 - q$. Therefore, we can apply the DP algorithm with the terminal action $J_N(x_N, y_N) = 0$. The demand distribution of the next period will be known with probability q . Hence we have:

$$J_k(x_k, y_k) = \min_{u_k \geq 0} \mathbb{E}_{w_k} [cu_k + b \max(0, w_k - x_k - u_k) + h \max(0, x_k + u_k - w_k) \\ + qJ_{k+1}(x_k + u_k - w_k, L) + (1 - q)J_{k+1}(x_k + u_k - w_k, S) | y_k]$$

where the cost function $g_k(x_k, u_k, w_k) = cu_k + b \max(0, w_k - x_k - u_k) + h \max(0, x_k + u_k - w_k)$. As we saw in class, the functions $J_k(\cdot, L)$ and $J_k(\cdot, S)$ are convex functions and hence their convex combination will be a convex function. Thus we can find a T_k^i which minimizes the convex function:

$$c\alpha + \mathbb{E}_w [b \max(0, w - \alpha) + h \max(0, \alpha - w) + qJ_{k+1}(\alpha - w, L) + (1 - q)J_{k+1}(\alpha - w, S) | y_k]$$

where y_k takes the values L and S .

Then the optimal policy is:

$$\mu^*(x_k, y_k) = \begin{cases} T_k^i - x_k, & \text{if } y_k = i, T_k^i > x_k \\ 0, & \text{otherwise} \end{cases}$$

where $i \in \{L, S\}$

2 Inventory Pooling

We want to compare the optimal expected cost between a decentralized and a pooled inventory system with n locations. Let the demand at each location i be independently, normally distributed with mean μ and variance σ^2 , i.e. $D_1, \dots, D_n \stackrel{iid}{\sim} N(\mu, \sigma^2)$. Then $\sum_{i=1}^n D_i \stackrel{d}{=} \sqrt{n}D_1 + \mu(n - \sqrt{n})$.

Let h and b denote the inventory holding cost and backorder cost, respectively. We already know that if $G(Q^*) = \mathbb{E}_D [h(Q^* - D)_+ + b(D - Q^*)_+]$ denotes the optimal expected cost for each location (with optimal order quantity $Q^* = \inf \left\{ Q \geq 0 : \mathbb{P}(D_1 \leq Q) \geq \frac{b}{b+h} \right\}$), then the optimal expected cost in the decentralized inventory system is

$$G_D(Q^*) = \sum_{i=1}^n G(Q^*) = nG(Q^*)$$

To find the optimal expected cost in the pooled inventory system $G_P(Q_P^*)$, we first need to determine the optimal order quantity Q_P^* under this system.

$$\begin{aligned}
Q_P^* &= \inf \left\{ Q \geq 0 : \mathbb{P} \left(\sum_{i=1}^n D_i \leq Q \right) \geq \frac{b}{b+h} \right\} \\
&= \inf \left\{ Q \geq 0 : \mathbb{P} (\sqrt{n}D_1 + \mu(n - \sqrt{n}) \leq Q) \geq \frac{b}{b+h} \right\} \\
&= \inf \left\{ \sqrt{n}X + \mu(n - \sqrt{n}) \geq 0 : \mathbb{P} (D_1 \leq X) \geq \frac{b}{b+h} \right\} \\
&= \sqrt{n} \inf \left\{ X \geq 0 : \mathbb{P} (D_1 \leq X) \geq \frac{b}{b+h} \right\} + \mu(n - \sqrt{n}) \\
&= \sqrt{n}Q^* + \mu(n - \sqrt{n})
\end{aligned}$$

With this we can now determine optimal expected cost in the pooled inventory system $G_P(Q_P^*)$:

$$\begin{aligned}
G_P(Q_P^*) &= \mathbb{E}_{\{D\}} \left[h(Q_P^* - \sum_{i=1}^n D_i)_+ + b(\sum_{i=1}^n D_i - Q_P^*)_+ \right] \\
&= \mathbb{E}_{\{D\}} [h((\sqrt{n}Q^* + \mu(n - \sqrt{n})) - (\sqrt{n}D_1 + \mu(n - \sqrt{n})))_+ \\
&\quad + b((\sqrt{n}D_1 + \mu(n - \sqrt{n})) - (\sqrt{n}Q^* + \mu(n - \sqrt{n})))_+] \\
&= \mathbb{E}_{\{D\}} [h(\sqrt{n}Q^* - \sqrt{n}D_1)_+ + b(\sqrt{n}D_1 - \sqrt{n}Q^*)_+] \\
&= \sqrt{n} \cdot \mathbb{E}_{\{D\}} [h(Q^* - D_1)_+ + b(D_1 - Q^*)_+] \\
&= \sqrt{n}G(Q^*)
\end{aligned}$$

It follows that

$$\frac{G_D(Q^*)}{G_P(Q_P^*)} = \frac{nG(Q^*)}{\sqrt{n}G(Q^*)} = \frac{n}{\sqrt{n}} = \sqrt{n}$$

This result means that the expected optimal cost of the decentralized system is \sqrt{n} -times as large as the expected optimal cost of the pooled inventory system under the given assumptions.

3 An Investment Problem

We want to find the optimal investment strategy in a situation where the investor can make N sequential investment decisions, each resulting in one of two possible outcomes: Either

(1) the invested money doubles (with probability $1/2 < p < 1$, or (2) the invested money is lost (with probability $1 - p$).

Let x_k denote the wealth at time k (initial wealth x_0), let $u_k \in U_k(x_k) = [0, x_k]$ be the investment (decision) at time k and let

$$w_k(u_k) = \begin{cases} 2u_k & \text{with probability } p \\ 0 & \text{with probability } (1 - p) \end{cases}$$

be the outcome of the investment at time k .

First, note that the state transition has the following form:

$$x_{k+1} = f(x_k, u_k, w_k) = x_k - u_k + w_k = \begin{cases} x_k + u_k & \text{with probability } p \\ x_k - u_k & \text{with probability } (1 - p) \end{cases}$$

The DP algorithm has the form (note that we can consider the logarithm of the investor's wealth after the N^{th} investment as the objective function without changing the optimal strategy):

$$J_N(x_N) = \ln(x_N)$$

$$\begin{aligned} J_k(x_k) &= \max_{u_k \in U_k(x_k)} \mathbb{E}_{w_k} [J_{k+1}(x_{k+1})] \\ &= \max_{u_k \in U_k(x_k)} [pJ_{k+1}(x_k + u_k) + (1 - p)J_{k+1}(x_k - u_k)] \end{aligned}$$

We want to find the strategy that yields the maximum expected wealth at time N , given initial wealth x_0 : $J_0(x_0)$.

First, consider the optimal strategy for a one-period investment horizon, i.e. $J_0(x_0) = J_{N-1}(x_{N-1}) = \max_{u_k \in U_k(x_k)} [p \ln(x_k + u_k) + (1 - p) \ln(x_k - u_k)]$. We can find the optimal investment strategy u_{N-1}^* using first-order conditions:

$$\begin{aligned}
\frac{\partial}{\partial u_{N-1}} J_{N-1}(x_{N-1}) &= 0 \\
\frac{\partial}{\partial u_{N-1}} [p \ln(x_{N-1} + u_{N-1}) + (1-p) \ln(x_{N-1} - u_{N-1})] &= 0 \\
\frac{p}{x_{N-1} + u_{N-1}^*} - \frac{1-p}{x_{N-1} - u_{N-1}^*} &= 0 \\
p(x_{N-1} - u_{N-1}^*) &= (1-p)(x_{N-1} + u_{N-1}^*) \\
u_{N-1}^* &= (2p-1)x_{N-1}
\end{aligned}$$

It follows that $J_{N-1}(x_{N-1})$ has the form:

$$\begin{aligned}
J_{N-1}(x_{N-1}) &= \max_{u_{N-1}} \mathbb{E}_{w_{N-1}} [\ln J_N(x_N)] \\
&= \max_{u_{N-1}} [p \ln(x_{N-1} + u_{N-1}) + (1-p) \ln(x_{N-1} - u_{N-1})] \\
&= p \ln(x_{N-1} + (2p-1)x_{N-1}) + (1-p) \ln(x_{N-1} - (2p-1)x_{N-1}) \\
&= p \ln(2p \cdot x_{N-1}) + (1-p) \ln((2-2p) \cdot x_{N-1}) \\
&= p \ln(2p) + \ln(x_{N-1}) + (1-p) \ln(2-2p) + \ln(x_{N-1}) \\
&= p \ln(2p) - p \ln(2-2p) + \ln(2-2p) + \ln(x_{N-1}) \\
&= A_{N-1} + \ln(x_{N-1})
\end{aligned}$$

where $A_{N-1} = p \ln(2p) - p \ln(2-2p) + \ln(2-2p)$ is independent of x_{N-1} . We see that $J_{N-1}(x_{N-1})$ contains the term $\ln(x_{N-1})$ and so the optimal strategy (known as "Kelly strategy") generalizes to all $k = 0, 1, \dots, (N-1)$ in the multi-period problem:

$$u_k^* = (2p-1)x_k$$

and therefore $J_k(x_k) = A_k + \ln(x_k)$ for some A_k independent of x_k .

4 Asset Selling with Maintenance Cost

Let's start by setting some notation. Let w_0, w_1, \dots, w_{N_1} be the offers the household gets. Given that the problem does not specify anything about investing the money from selling the house we will assume that such money does not get any interest rate from any possible investment. Let T denote the terminate state. Let $x_k = T$ at some time $k \leq N-1$ denote that the house has already been sold. Likewise, let $x_k \neq T$ at some time $k \leq N-1$ denote

that the house has not been sold yet.

Let's now identify the variables that define the DP algorithm that we will use in this exercise:

- x_k : state of the system at period k , which is the amount of money that the household gets at such period.
- u_k : control variable at period k . In this case the household can take two actions: sell or not sell. That is $u_k \in \{u_k^1(\text{sell}), u_k^2(\text{not sell})\}$
- w_k : uncertainty at time k , which corresponds to the offers.

Taking into account the fact that the rejected offers can be accepted in the future, the dynamics of the DP algorithm are:

$$x_{k+1} = \begin{cases} T & \text{if } x_k = T, \text{ or if } x_k \neq T \text{ and } u_k = u^1 \\ \max(x_k, w_k) & \text{otherwise} \end{cases}$$

and the reward function is

$$\mathbb{E}_{w_k} \left\{ g_N(x_N) + \sum_{k=0}^{N-1} g_k(x_k, u_k, w_k) \right\}$$

where

$$g_N(x_N) = \begin{cases} x_N & \text{if } x_N \neq T \\ 0 & \text{otherwise} \end{cases}$$

$$g_k(x_k, u_k, w_k) = \begin{cases} x_k & \text{if } x_N \neq T \text{ and } u_k = u^1 \\ -c & \text{if } x_N \neq T \text{ and } u_k = u^2 \\ 0 & \text{if } x_N = T \end{cases}$$

Therefore, the DP algorithm is,

$$J_N(x_N) = \begin{cases} x_N & \text{if } x_N \neq T \\ 0 & \text{otherwise} \end{cases}$$

$$\begin{aligned}
J_k(x_k) &= \begin{cases} \max_{u_k \in U_k(x_k)} \mathbb{E}_{w_k} \{g_k(x_k, u_k, w_k) + J_{k+1}(x_{k+1})\} & \text{if } x_N \neq T \\ 0 & \text{if } x_N = T \end{cases} \\
&= \begin{cases} \max_{w_k} \mathbb{E} \{g_k(x_k, u_k^1, w_k) + J_{k+1}(x_{k+1}), g_k(x_k, u_k^2, w_k) + J_{k+1}(x_{k+1})\} & \text{if } x_N \neq T \\ 0 & \text{if } x_N = T \end{cases} \\
&= \begin{cases} \max\{\text{Revenue from selling, Expected revenue from not selling}\} & \text{if } x_N \neq T \\ 0 & \text{if } x_N = T \end{cases} \\
&= \begin{cases} \max\{x_k + 0, \mathbb{E}_{w_k} \{J_{k+1}(w_k) - c\}\} & \text{if } x_N \neq T \\ 0 & \text{if } x_N = T \end{cases}
\end{aligned}$$

This leads to the one-stopping set of the following form:

$$\begin{aligned}
T_{N-1} &= \{x | x > \mathbb{E}_{w_k} (J_N(x_N) - c)\} \\
&= \{x | x > \mathbb{E}_{w_k} (\max(x_{N-1}, w_{N-1}) - c)\} \\
&= \{x | x > \sum_{j=1}^n p_j \max(x_{N-1}, w_{j,N-1}) - c\} \\
&= \{x | x > \sum_{j=1}^n p_j \max(x, w_j) - c\}
\end{aligned}$$

Note that the last line of the previous mathematical development comes from the fact that the function $\sum_{j=1}^n p_j \max(x_{N-1}, w_{j,N-1}) - c$ is non-increasing which implies that T_{N-1} is absorbing in the sense that if a state belongs to T_{N-1} and termination is not selected, then the next state will also be in T_{N-1} . If we define $\bar{\alpha}$ to be

$$\bar{\alpha} = \sum_{j=1}^n p_j \max(x, w_j) - c$$

then the optimal policy is defined by,

$$\mu_k^*(x_k) = \begin{cases} u^1 & \text{if } x_k > \bar{\alpha} \\ u^2 & \text{if } x_k < \bar{\alpha} \end{cases}$$

5 Scheduling Problem

5.1 Part (a)

We solve this problem using list indexing. Let L be the optimal order of answering the questions. Let i and j be the k^{th} and $(k+1)^{st}$ questions in the optimally ordered list L .

$$L = (i_0, \dots, i_{k-1}, i, j, i_{k+2}, \dots, i_{N-1})$$

We can then calculate the expected return for answering the questions in this order.

$$\begin{aligned} \mathbb{E}[\text{reward of } L] &= \mathbb{E}[\text{reward of } \{i_0, \dots, i_{k-1}\}] \\ &\quad + p_{i_0} p_{i_{k-1}} p_i (R_i + p_j R_j - (1 - p_j) F_j) - (1 - p_i) F_i \\ &\quad + p_{i_0} p_{i_k} p_i p_j \mathbb{E}[\text{reward of } \{i_{k+2}, \dots, i_{N-1}\}] \end{aligned}$$

Now we consider the is were questions i and j are interchanged.

$$L' = (i_0, \dots, i_{k-1}, j, i, i_{k+2}, \dots, i_{N-1})$$

Since L is optimal, $\mathbb{E}[\text{reward of } L] \geq \mathbb{E}[\text{reward of } L']$ This is equivalent to

$$\begin{aligned} p_i (R_i + p_j R_j - (1 - p_j) F_j) - (1 - p_i) F_i &\geq p_j (R_j + p_i R_i - (1 - p_i) F_i) - (1 - p_j) F_j \\ \implies \frac{p_i R_i - (1 - p_i) F_i}{1 - p_i} &\geq \frac{p_j R_j - (1 - p_j) F_j}{1 - p_j} \end{aligned}$$

So questions should be answered in order of decreasing

$$\frac{p_i R_i - (1 - p_i) F_i}{1 - p_i}$$

5.2 Part (b)

With a no cost option of stopping, the questions would be answered in the same order as there would be no change to the argument above. We must now consider when the player should stop answering questions. Before each question they have two options stop answering questions or answer the next question. The player should chose the option with the higher expected reward. Clearly the expected reward for stopping is 0. The optimal stopping space would be

$$T_k = \{x | 0 \leq p_k R_k - (1 - p_k) F_k + J_{k+1}(x_k + p_k R_k)\}$$

with

$$\begin{aligned} J_n(x_n) &= 0 \\ J_k(x_k) &= \max\{0, p_k R_k - (1 - p_k) F_k + J_{k+1}(x_k + p_k R_k)\} \end{aligned}$$