Information acquisition of new technology performance for maintenance/investment decisions

Thi Phuong Khanh Nguyen, Bruno Castanier, Thomas G. Yeung

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T.P.K.Nguyen, Bruno Castanier and Thomas G.Yeung
Industrial Engineering and Automatic Control Department
Ecole des Mines de Nantes, IRCCyN
F-44307 Nantes Cedex 3, France
pnguye09@mines-nantes.fr

Abstract—**The possibility of new technology occurrence has an important impact on the maintenance/ replacement decision. Therefore, a challenge in maintenance decision making is to determine maintenance policy and replacement investment plan under an uncertainty of technology improvement. In each period, we must decide whether to gather additional information on the potential improvement of a new technology, and then chose the appropriate action for the asset (Do Nothing, Maintenance or Replacement). To formulate this scenario, we use a non stationary Markov Decision Process (MDP) model and provide some properties of the optimal policy based on a given set of numerical examples.**

Keywords-information acquisition; maintenance/ investment; MDP; technology breakthrough.

I. INTRODUCTION

Renewing a system that becomes obsolete because of a new technology cannot be economically profitable. The level of knowledge in the future technologies becomes preponderant information for strategic decisions. Therefore, a few studies have looked into developing the most appropriate model for technology adoption based on the information acquisition.

In an early study [1], the authors addressed the question when to adopt the innovation, whether to do nothing while waiting for the market transition or to purchase information and decide based on acquired information. However, the main limitations of this model are the assumptions that the information is perfect and that transition matrix is known before. Then, in [2] McCardle considered a dynamic programming model, in which a decision marker decided whether to gather information or to outright grasp/ reject an innovation. Nonetheless, the study is restrictive in the form of the profitability distribution and signal process. In 2009, by considering a probability distribution as state variable, Ulu and Smith [3] showed the limitation of considering a univariate setting of technology's expected benefit in McCardle model. That is, a rise in the technology's expected benefit or the first order stochastic dominance (FOSD) improvement in the distribution on benefits does not necessarily imply an increase in the value function nor does it show the necessity of the new technology adoption. In addition, with [4], to address the information acquisition problem for determining whether to take a business opportunity or not, the authors developed a general model similar to Ulu and Smith’s model with an additional consideration of the probability of losing this opportunity. Nevertheless, these previous models only analyze the decision process based on an available innovative technology without considering a technology that has not yet appeared. In addition, they are strictly economically oriented while in the industrial engineering, considering the information purchasing about new technology for maintenance/replacement policy is an unexplored area. The authors in [5], [6] showed that the technology evolution has a significant impact on the optimal replacement/ maintenance policy even when the next generation technology has not yet appeared. Moreover, planning maintenance/replacement action under uncertainty of the profitability level of new technology may reduce decision accuracy. Hence, common errors related to a lack of knowledge into upcoming technological developments are either the decision of an early replacement by a near-obsolete technology or the decision to defer maintenance or replacement in waiting in vain for a new and more efficient technology. Although the first error can be regarded as more critical as positioning itself at the strategic decision level, volatility and aggressiveness of the markets due to excessive competition require the construction of appropriate decision models that meets the operational and strategic requirements. In each epoch, the manager will decide if the purchase of information on the new technology’s profitability level is needed. And then based on the current information, he/ she decides an adequate action. The updating process after the information acquisition is modeled as detailed in [3] and [4] using Bayes rules with the likelihood function of the information. With the increasing of the new technology’s apparition probability over time, we propose a discrete time non-stationary Markov Decision Process (MDP) formulation to determine the optimal action plan. The remainder of this paper is structured as followed: Section II is devoted to the mathematical formulation. In Section III, the performance of our model is discussed through numerical examples. Finally, a conclusion and future work are discussed in Section IV.

II. MODEL AND ASSUMPTIONS

A. Problem statement

Consider a repairable machine that operates continuously from the new state, $X = x_0$, until a failure state, $X = z$. In the failure state, the machine continues to operate but unprofitably. To reveal the deterioration level, periodic inspections are performed. The inspection times define the decision epochs where a choice in the three following actions has to be done according to the observed deterioration level x:

- Do nothing (*DN*): The machine continues to deteriorate until next decision epoch and generates a profit $g(x)$. Note that $g(x)$ is the expected accrued profit within a period and depends on the deterioration state at the beginning of that period. In case of failure, the do nothing action is still allowed but the profit in the next decision epoch is assumed to be negative.
- Maintenance (*M*) restores the machine to a given deterioration level, x_M. An increasing maintenance cost in the deterioration, $c_M(x)$, is incurred and as we assume that the maintenance time is negligible, then, in the next decision interval, the machine deteriorates from the level x_M and generates a profit $g(x_M)$.
- Replacement (*R*) the equipment by new one. The cost of such a replacement is given by the difference between the purchase price of the new machine c_0 and the salvage value $b(x)$. After the replacement whose time is negligible, the new machine generates a profit $g(x_0)$.

Under technological evolution, a new machine's appearance can occur on the market with an increasing probability over time, p_n. So, in each period, before choosing the appropriate action (*DN*, *M* and *R*) the manager decides whether to gather additional information about the new technology's performance or not.

We define $\theta \in \Theta$, the expected total profit of the investment in new technology (after subtracting the purchasing cost) with i be the level of this profit. The uncertainty in θ_i value or simply the belief in θ_i is modeled by a probability distribution π over Θ. The information purchasing time is also assumed to be negligible and this action is described as followed:

- Information acquisition (*A*): The manager pays information cost c_s and get an information s_j, $s_j \in S$, drawn with likelihood function $L(s|\theta)$. We define $f(s_j,\pi)$ is the predictive distribution for information s_j :

$$f(s_j, \pi) = \sum_i L(s_j|\theta_i)\,\pi(\theta_i) \tag{1}$$

Having information s_j, the manager then updates her prior π using Bayes's rules and obtain a posterior $\pi'(\pi, s_j)$, given by :

$$\pi'(\theta_i;\pi, s_j) = \frac{L(s_j|\theta_i)\pi(\theta_i)}{f(s_j, \pi)} \tag{2}$$

Then, the manager can choose one of the actions (*DN*, *M*, *R*) based on the new beliefs.

B. Model formulation

We define (x, π) be the system state. Let $V_n^N(x, \pi)$ denoted the maximum expected discounted value from the decision epoch n to the last epoch N given that the new technology has not yet appeared. $\widehat{V}(x, \theta_i)$ represents the maximum expected discounted value given that the new technology has appeared with the benefit θ_i. With discount factor β, the optimization problem is:

$$V_n^N(x, \pi) = \max\ \{A_n^N(x, \pi),\ O_n^N(x, \pi)\} \tag{3}$$

With:

$$O_n^N(.) = \max\{DN_n^N(.),\ M_n^N 1_{\{x < x_M\}}(.),\ R_n^N(.)\} \tag{4}$$

$$A_n^N(x, \pi) = -c_s + \sum_i f(s_j,\pi) O_n^N(x,\pi'(\pi, s_j)) \tag{5}$$

$$DN_n^N(x, \pi) = \begin{cases} g(x) + \\ \beta \begin{pmatrix} (1-p_n) \sum_{x'} P(x'|x) V_{n+1}^N(x',\pi) + \\ p_n \sum_i \pi(\theta_i) \sum_{x'} P(x'|x) \widehat{V}(x',\theta_i) \end{pmatrix} \end{cases} \tag{6}$$

$$M_n^N(x, \pi) = -c_M(x) + DN_n^N(x_M,\pi) \tag{7}$$

$$R_n^N(x, \pi) = -c_0 + b(x) + DN_n^N(x_0,\pi) \tag{8}$$

And

$$\widehat{V}(.) = \max \begin{Bmatrix} \widehat{DN}(.) = g(x) + \beta \sum_{x'} P(x'|x) \widehat{V}(x',\theta_i) \\ \widehat{M}(.) = -c_M(x) + \widehat{DN}(x_M,\theta_i);\ \forall x > x_M \\ \widehat{R}(.) = max\{\widetilde{R}(x),\ \theta_i + b(x)\} \end{Bmatrix} \tag{9}$$

Note that after technology breakthrough, the manager can weigh the benefit of using the current asset and the profit in new technology investment. If the purchasing cost of new technology is very high, its expected profit θ_i is low, then we can reject it and replace the current asset by the same technology ($\widetilde{R}(x)$).

Let $\widetilde{V}(x)$ be the maximum expected discounted value over infinite horizon when we do not consider the possibility of new technology apparition. We have:

$$\widetilde{V}(x) = max \begin{Bmatrix} \widetilde{DN}(x) = g(x) + \beta \sum_{x'} P(x'|x) \widetilde{V}(x') \\ \widetilde{M}(x) = -c_M(x) + \widetilde{DN}(x_M);\ \forall x > x_M \\ \widetilde{R}(x) = -c_0 + b(x) + \widetilde{DN}(x_0) \end{Bmatrix} \tag{10}$$

On the other hand, we define a time horizon of interest for the new technology appearance for which beyond this, we no longer consider the apparition probability. Hence, we consider $V_n^N(x, \pi) = \widetilde{V}(x)\ \ \forall \pi$.

III. NUMERICAL EXEMPLES

In this section, we present numerical examples to illustrate the performance of our model.

A. Input parameters

We consider an asset that has five degradation levels with the failure state z = 5. After maintenance action, the system is restored to x_M = 2. The accumulated gain in a period and Markovian deterioration transition probability matrix for the current technology are respectively:

$$g = [200 \quad 160 \quad 100 \quad 20 \quad -70]$$

$$P = \begin{bmatrix} 0.8 & 0.2 & 0 & 0 & 0 \\ 0 & 0.8 & 0.2 & 0 & 0 \\ 0 & 0 & 0.8 & 0.2 & 0 \\ 0 & 0 & 0 & 0.5 & 0.5 \\ 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

The maintenance cost is an increasing function while the salvage value is a decreasing function in deterioration state. With v, h_1, h_1 are constant, we have:

$$c_M(x)=v + h_1(x - x_M) \tag{11}$$

$$b(x)=h_2(m - x) \tag{12}$$

We define the appearance probability of new technology at decision epoch n+1 as an increasing function in time. This assumption is consistent with the character of technological breakthrough.

$$p_{n+1}=1- \varepsilon\delta^n; \qquad \delta, \varepsilon \leq 1 \tag{13}$$

The ε factor reflects the non-apparition probability of new technology at the next decision epoch. Factor δ characterizes the increasing rate of the appearance probability of new technology over time.

We assume that the new technology will appear with two benefit levels $\theta_1 < \theta_2$ and that two types of information s_j (s_2 is more favorable than s_1) will obtained with likelihood function (L). With a_1, $a_2 \geq$ 0.5, we have:

$$L = \begin{bmatrix} L(s_1|\theta_1) & L(s_2|\theta_1) \\ L(s_1|\theta_2) & L(s_2|\theta_2) \end{bmatrix} = \begin{bmatrix} a_1 & 1\text{-}a_1 \\ 1\text{-}a_2 & a_2 \end{bmatrix}$$

TABLE I. THE INPUT PARAMETERS

Discount factor & Appearance probability	β	ε	δ
	0.9	0.7	0.98
Maintenance cost & Salvage value	v	h_1	h_2
	80	50	20
Purchase price of current tech & New tech profit	c_0	θ_1	θ_2
	400	1200	2100

B. Analysis from numerical experiments

With time horizon N = 100 and input parameters given in Tab. I, at any decision epoch n, the optimal maintenance/ replacement policy prescribes:

- After new technology occurrence with the benefit level θ_1 = 1200: we do nothing when deterioration x=1,2 and replace the machine by new technology when $x \geq 3$.
- After new technology occurrence with the benefit level θ_1 = 2100: we replace immediately the machine by new technology and do not have any interest in its deterioration level.

When new technology has not yet appeared, our policy is non stationary over time because the decisions are influenced by an increasing of new technology's apparition probability. The optimal policies for the first decision epoch are given in the Fig. 1. We consider:

- Case I: Imperfect information with its purchase cost c_s = 10 and Likelihood function (L) defined by a_1=a_2=0.8
- Case II: Perfect information with its purchase cost c_s= 10 (a_1=a_2=1)
- Case III: Imperfect information with its low purchase cost c_s= 1 and Likelihood function (L) defined by a_1=a_2=0.8
- Case IV: Low quality information - Likelihood function (L) defined by a_1=a_2=0.5.

For each subfigures of Fig. 1, the optimal option in the action set {A-Information Acquisition, DN-Do nothing, M-Maintenance, R- Replacement} is a function of the current deterioration state, x (vertical axis), and the probability of a low improvement in the new technology, $\pi(\theta_i)$ (horizontal axis). We find that the information acquisition is only made when the manager is weighing between two options (Do nothing and Maintenance option; or Maintenance and Replacement option). For example, in Fig. 1a, we only purchase information when deterioration state is x = {4, 5}. Furthermore, when $\pi(\theta_1)$ is small, the maintenance option is used for waiting the apparition time of new technology with high profit level. As the value of $\pi(\theta_1)$ increases, after the M-region, we gather additional information (A-region), and finally, replacement is made.

Then, we examine the impact of better information on the optimal policy. Consider the A-region in the Case I, II and IV, we find that increasing the information quality expands the information acquisition region. In fact, the A-region in the Case II of perfect information is the largest region while in the Case III of low quality information; the optimal policy suggests not buying information even if its cost is lower. In addition, a decline in the information cost also expands the A-region. For example, in Fig. 1.c the A-region is not only larger than that in Fig. 1.a at x = 4, 5 but also appears at x = 3.

Finally, we examine the impact of new technology's apparition probability on the value of purchasing information (*A*). The Fig. 2 presents the difference between the maximal value in the case where we consider further the *A*-option and in the case without the *A*-option. That is also the *A*-option's objective value. We find that due to the *A*-option, the maximum objective value function is enhanced. In addition, the apparition probability of new technology has certain influence on the *A*-option value. However, across deterioration x, this influence is non-monotone. Consider the Fig. 2 that is divided into five parts, corresponding to five deterioration state x, we find that when $x = 5$ the *A*-option value is increasing in the apparition probability of new technology (p_n). On the other hand, at the second part ($x = 2$), the *A*-option value is increasing when p_n is rising from $p_n = 0.3$ to $p_n = 0.4$ but decreasing when p_n varies from 0.4 to 0.6. So, the rising in apparition probability of new technology does not necessarily imply an increase in the *A*-option value.

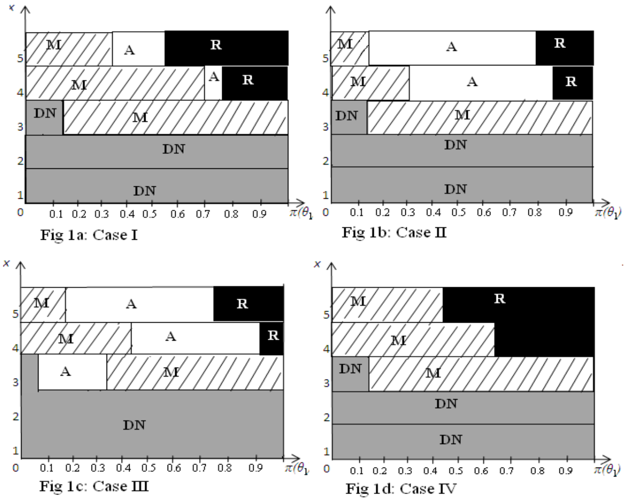

Figure 1. The optimal policies

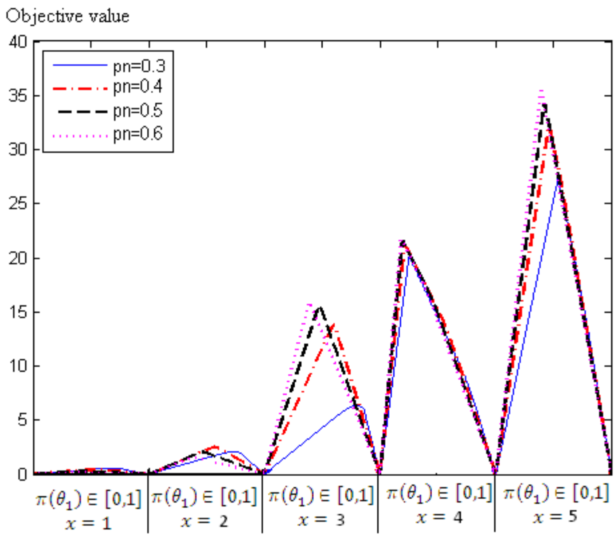

Figure 2. Impact of new technology's apparition probability on the Value of Information acquisition option

IV. CONCLUSION

In this paper, we proposed a model that allows managers to take into account the information acquisition option in the maintenance/ replacement problem under the technological development. It determines the maintenance strategy from the operator's point of view, based on the parametric performance of the system. In addition, it allows the manager to consider the necessity of information acquisition on the new technology's profitability as well as to examine the impact of technology change on the action planning even when the breakthrough point has not yet appeared.

We then used stochastic dynamic programming to solve for the optimal policy as a function of performance and cost. Finally, we presented numerical examples to illustrate performance of our model and to consider the influence of the parameters characterized the information quality and the apparition probability of new technology on the optimal decisions. Through numerical example results, we have shown that the importance of considering new technology information acquisition when planning the maintenance/ replacement action for the asset. In fact, the information purchasing option helps to improve the maximal value function. It is more important when the information is better or cheaper. A non-trivial result is also deduced. That is, the increasing in apparition probability of new technology does not show the necessity of the purchasing information.

However, these above results are only the preliminary conclusions recorded by the illustrated numerical examples. In future work, we will study structural properties of the policy. We are also interested in its sensitivity through characterized parameters of model. Furthermore, the evolution of technology's benefit over time could be considered as well as its impact on the optimal decision. Finally, a more efficient algorithm for optimizing the information acquisition for maintenance/ replacement policy should also be developed.

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