OPTIMAL MAINTENANCE SERVICE CONTRACT FOR REPAIRABLE EQUIPMENT INVOLVING THREE PARTIES – MANUFACTURER, AGENT AND CUSTOMER

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Abstract: Every engineering object (equipment or machine) is unreliable in a sense that it will degrade with age and/or usage, and eventually will fail. Maintenance actions are required to maintain a good condition of the engineering object. The engineering object of interest is heavy equipment used in an open coal mining such as dragline, dump trucks, excavators, etc. We consider that the heavy equipment is repairable and sold with warranty. Preventive maintenance (PM) and corrective maintenance (CM) actions are needed to keep the equipment in a satisfied condition. In some cases, PM is one package with warranty and hence the maintenance actions are borne by the manufacturer during the warranty, but after the warranty ends, they are borne by the customer (the owner of the equipment) and maintenance can be done in house or by outsource. As maintenance is not a core business of the mining company, often it is outsourced to an external agent (or original equipment manufacturer (OEM)). We examine a situation where the OEM offers PM and/or CM only in the warranty period and after the expiry of the warranty several maintenance options are offered by an agent. Hence, during a life cycle of the equipment, several combinations of maintenance service options offered by OEM and Agent are available for the customer to be selected. The decision problem for OEM or Agent is to determine the price of each option offered. In this paper, we construct a mathematical model that integrates the three decision problems using a Stackelberg game theory formulation. The optimal decision of the maintenance service contract for each party is obtained using a bi-level programming optimization with (i) upper-level problem for maximization manufacturer's profit with related constrains (ii) lower-level problem for maximization agent's profit with consumer's utility function as constrains. Some numerical examples and managerial insights are presented to illustrate the decision problems studied in this paper.

Keywords: Maintenance Service Contract, Three-parties, Bi-level Optimization, Reliability.

I. INTRODUCTION

A maintenance Service Contract (MSC) is defined as a binding agreement between the customer and the service agent (SA) in which the SA agrees to carry out maintenance services with a scope of work and a price specified in the contract for an engineering object for a period of time. MSC is usually associated with the maintenance of engineering objects such as product engineering, factory machinery and infrastructure (Murthy & Jack, 2014). We consider that every engineering object is unreliable in sense that it will degrade with age and/or use, and eventually will fail. Maintenance actions are required to maintain the good condition of the engineering object. One can divide engineering objects into two groups – non-repairable and repairable items. When a repairable item fails, it can be repaired to a functioning state. But for a non-repairable item, the failed item has to be replaced when it fails. The engineering object of interest is heavy equipment used in mining sites. In general, heavy equipment such as draglines, dump trucks, excavators are operated mainly to support the operations of loading (loading) and transport (hauling) mining materials. Transportation (hauling) is an activity that absorbs the cost is quite large (about 60-70%) of the total cost open pit mining operation. To achieve the target production per year, it needs to provide the high degree of readiness (availability) of the heavy equipment. Effective maintenance actions are required to achieve high degree of availability. There are two types of maintenance actions - preventive maintenance (PM) and corrective maintenance (CM)). PM and CM can be done in house or by outsource. As maintenance is not a core business of the mining company, then often it is outsourced to an external agent (or original equipment manufacturer (OEM)). Another reason to outsource is that doing it in house requires high investment for maintenance facilities and high qualification of maintenance specialists, and hence it is more economical to outsource. Study on maintenance contracts have been received much attention in the literature, and they can be grouped into two categories – (i) MSC for a non-repairable system (See Esmaili, et.al. (2014)) and (ii) MSC for a repairable system (Sahin & Polatoglu (1998), Murthy & Ashgarizadeh (1999), Ashgarizadeh & Murthy (2000), Rinsaka & Sandoh (2006), Jack & Murthy (2007)).

Most of works on MSC deal with service contract involving two parties – i.e. the manufacturer (or SA) and the customer. Here, the decision problem for SA and the decision problem for the customer are interdependent and need to model the decision problems using a game theory formulation (Nash and Stackelberg game theory formulations are often used). Only the work by Esmaili, et.al. (2014) deals with MSC which involves three parties – the manufacturer, SA and the customer. But the engineering object considered is a non-repairable item. In this paper, we extend the case studied in Esmaili, et.al. (2014) for a repairable item, and hence it needs to incorporate a preventive maintenance policy. We consider an imperfect PM policy which reduces failure rate of the dump truck for each PM carried out.

This paper is organized as followed. Section 2 provides notations includes decision variables and parameters. The model formulation is given in section 3, this includes warranty policy, MSC, equipment and repair scheme, the decision problem model of each party, bi-level optimization approach and solution procedure. Section 4 provides results and discussion include numerical example and managerial insights. Finally conclusions are drawn in the last section.

II. NOTATIONS

The following notations will be used in model formulation.

2.1. Decision Variables

P_{wi}	warranty price, option $i = 1,2$ from OEM
P_a	maintenance price
C_{ir}	CM cost charged by the agent to the customer under option i of agent, $i = 1,3$
C_{ip}	CM cost charged by the agent to the customer under option i of agent, $i = 1,3$
z_i, y_i	zero-one decision variables when option i of customer is selected

2.2. Parameters

P_s	sale price received by the OEM
L	lifetime of product
C_{0p}	PM cost incurred by OEM/agent
C_r	CM cost incurred by OEM/agent
N_1	number of failures during warranty period by OEM
N_2	number of failures during warranty period by agent
N_3	number of failures during $[W, L)$
$r_0(t)$	failure rate
$\Lambda(t)$	cumulative distribution function of failure rate
$r_j(t)$	failure rate at j^{th} time after j^{th}PM
m	number of PM during $[0, W)$
k	number of PM during $[W, L)$
δ_{iA}	reduction amount caused by agent
δ_{iM}	reduction amount caused by OEM
R	quantitative satisfaction/revenue of customer under each option
ρ_{Mi}	profit of OEM under option i, $i = 1,2$
ρ_{Ai}	profit of agent under option i, $i = 1,2,3$
$U_i(C)$	utility function of customer under option i, $i = 1,2,3$

III. MODEL FORMULATION

3.1. Warranty Policy

A dump truck is sold with a warranty in which PM may or may not be one bundle of the warranty. The warranty provided by the manufacturer is a non-renewing free repair warranty and hence all failures under warranty is repaired without charge to the consumer. We consider the case where the manufacturer offers the consumer two options – (i) warranty and PM is one package or (ii) warranty without PM. In option (i), both PM and CM during the warranty period (W) are borne by the manufacturer whilst in option (ii) the manufacturer is responsible for CM and the consumer for PM. Hence, the options offered by the manufacturer (or OEM) are:

Option M_1 : OEM provide warranty and PM
Option M_2 : OEM provide warranty without PM

After the expiry of the warranty (meaning that from W to the life cycle (L) of the dump truck), all maintenance actions become the responsibility of the customer.

3.2. Maintenance Service Contract (MSC)

It is assumed that Service Agent (SA) offers a partial (only CM) or full coverage (PM and CM) of MSC. Before or after the warranty period expires. As a result, there are three options of MSC offered by SA.

Option A_1 : The warranty is offered without PM, and hence SA performs PM during $[0, L)$ at price C_{1p}. After the warranty expires, SA preforms CM with CM cost per failure, C_{1r}.
Option A_2 : The warranty is one bundle with PM. SA perform PM and CM during $[W, L)$ at a fixed price P_a.
Option A_3 : The warranty is one bundle with PM. SA performs PM during $[W, L)$ at a fixed price C_{3p}but CM during $[W, L)$ with cost per failure,C_{3r}.

Both OEM and SA need to determine the optimal pricing structure for each option so that to maximize their profits.

3.3. Equipment and Repair

As mentioned before that the equipment under consideration is a dump truck used in a mining industry. Failure of the equipment is random and is modeled using black box approach (observe only functioning/failed state).

If$T$is a random variable representing time to the first failure of the equipment, then T is modelled by the cumulative distribution function of failure $F(t)$. The

hazard rate function associated with $F(t)$ is $r(t)$, and the cumulative hazard rate $\Lambda(t) = \int_0^t r(x)\,dx$.
Second failure and sequence failures are influenced by the imperfect PM done. One can model the impact of PM either by reduction in (i) virtual age or (ii) intensity function (Jiang dan Murthy, 2008). We use (ii) and describe as follows. PM is performed periodically at the time t_i, $1 \le i \le k$, with $t_i < t_j$ for $i < j$ and $t_0 = 0, t_k = L$. Hence, the total number of PM is k times in $[0, L)$. The i-th PM leads to the intensity function down by δ_i and the limit of δ_i is given by:

$$0 \le \delta_i \le r_{i-1}(t_j) - \sum_{i=1}^{j-1} \delta_i \qquad (1)$$

Define $N(t)$ as the expected number of failures during $[0, t)$. The expected failures during $[t_{j-1}, t_j)$ is given by:

$$N_j = \int_{t_{j-1}}^{t_j} r_{j-1}(t)dt$$

$$= \left[\Lambda(t_j) - \Lambda(t_{j-1})\right] - (t_j - t_{j-1}) \sum_{i=0}^{j-1} \delta_i \qquad (2)$$

It is assumed that all failures are fixed by a minimal repair so that the repair does not affect the intensity function. As a result, failures in $(0, L)$ follow a Non Homogeneous Poisson Process (NHPP) with intensity function $r(t)$. $r(t)$ is an increasing function of t (IFR). IFR distributions are Weibull, Gamma etc. In this paper, we use the Weibull distribution.

3.4. Decision Problem Model

We consider MSC in which three parties involved - i.e. the manufacturer (OEM), the SA and the customer. The decision problems for OEM, SA and the customer are interdependent, and we model using a Stackelberg game theory formulation where each party will find the best option to maximize its profit We obtain each decision problem model as follows.

3.4.1. The OEM's Model

Based on the OEM's offered, the decision models for the OEM are described in the following two sections.
A.1. OEM's Profit 1 = sale price + warranty price – (CM cost) x expected number of failures during the warranty period – (number of PM [0,W) x PM cost)
i.e.

$$\rho_{M1}(P_{w_1}) = P_s + P_{w_1} - (C_r)E[N_1] - m\,C_{0p} \qquad (3)$$

A.2. OEM's Profit 2 = sale price + warranty price – (repair cost x expected number of failures during the warranty period) given by

$$\rho_{M2}(P_{w2}) = P_s + P_{w2} - C_r E[N_2] \qquad (4)$$

When the customer chooses the option M2, PM carried out by an agent is considered as a lower quality than that of PM done by OEM and hence δ_{iA} ($\delta_{iA} < \delta_{iM}$)), and the price is cheaper. Thus, $E[N_2]$ is different in value to $E[N_1]$ but has the same formulation.

3.4.2. The Agent's Model

The decision models for the Agent are described in the following three sections.
B.1. Agent's Profit 1 = (revenue of repairing failed product after expiration of warranty – repair cost) x expected number of failures after warranty period expiration + (revenue PM $[0, L)$ – (number of PM x PM Cost)
i.e.

$$\rho_{A1}(C_{1r}, C_{1p}) = (C_{1r} - C_r)E[N_3] + (C_{1p} - k\,C_{0p}) \qquad (5)$$

B.2. Agent's Profit 2 = maintenance price-repair cost for agent x expected number of failures after warranty period expired– (revenue PM-(number of PM (W,L) x PM Cost))
i.e

$$\rho_{A2}(P_a) = P_a - C_r E[N_3] - \left((k-m)\,C_{0p}\right) \qquad (6)$$

B.3. Agent's Profit 3 = (revenue of repairing failed product after expiration of warranty -repair cost) x expected number of failures after warranty period expiration+ (revenue PM – (number of PM (W,L) x PM Cost))
i.e

$$\rho_{A3}(C_{3r}, C_{3p}) = (C_{3r} - C_r)\,E[N_3] + (C_{3p} - (k-m)\,C_{0p}) \qquad (7)$$

3.4.3. The Customer's Model

Because OEM offers two options and SA providesthree types of maintenance packages tothe consumer, and hence the consumer has three options to choose:
C.1. Customer's Monetary Return 1 = (revenue obtained by the product – sale price – warranty price – repair and PM cost after warranty period expiration)
i.e.

$$\rho_{C1} = (R - P_s - P_{w1} - P_a) \qquad (8)$$

The utility function based on the customer's monetary returns and the customer's behavior to the risk can be written as follows (Murthy & Jack, 2014):

$$U_i(C) = \begin{cases} \dfrac{1 - e^{-\gamma_i \rho_{C_i}}}{\gamma_i}, & \gamma_i \neq 0 \\ \rho_{Ci}, & \gamma_i = 0 \end{cases}$$

If the customer is risk-neutral then $U(C) = \rho_C$. And $\gamma_i > 0$ for risk-averse choice.

$$U_1(C) = \frac{1 - e^{-\gamma_1((R - P_s - P_{w1} - P_a))}}{\gamma_1} \qquad (9)$$

C.2. Customer's Monetary Return 2 = (revenue obtained by the product – sale price – warranty price –PM cost – repair cost after warranty period expiration per failure) i.e.

$$\rho_{C2} = \left(R - P_s - P_{w1} - C_{3p} - C_{3r}E[N_4]\right) \quad (10)$$

$$U_2(C) = \frac{1 - e^{-\gamma_1((R-P_s-P_{w1}-C_{3p}-C_{3r}E[N_4]))}}{\gamma_1} \quad (11)$$

C.3. Customer's monetary return 3 = (revenue obtained by the product – sale price – warranty price –PM cost – repair cost after warranty period expiration per failure)
i.e.

$$\rho_{C3} = \left(R - P_s - P_{w2} - C_{1p} - C_{1r}E[N_4]\right) \quad (12)$$

$$U_3(C) = \frac{1 - e^{-\gamma_1((R-P_s-P_{w2}-C_{1p}-C_{1r}E[N_4]))}}{\gamma_1} \quad (13)$$

3.5. Bi-level Optimization Approach

In this section, we model the interactions between the manufacturer, agent and customerunder two power scenarios: OEM-Stackelberg and Agent-Stackelberg. The optimization problems involve two levels that are (i) upper-level problem (OEM is a leader and SA as follower) (ii) lower-level problem (SA is a leader and the consumer as follower). A Bi-level optimization approach is used to obtainthe optimal solutions (see Fig.1).

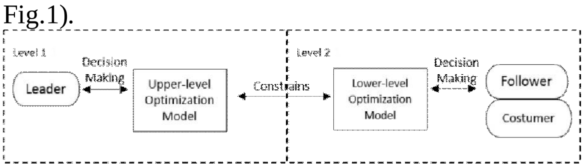

Fig.1. The process of decision-making by the leader (OEM) and the follower (Agent)

<u>**Upper-level problem *:* OEM-Stackelberg Model**</u>

Given P_a, and CM costs$C_{1r}, C_{3r}$and PM costsC_{1p}, C_{3p}do optimization for maximizing OEM profit$\rho_M(P_{w1}, P_{w2})$ based on the input values earlier. Thus, the OEM model can be expressed as follows:

$$\max \rho_M(P_{w1}, P_{w2}) = y_1\left\{P_s + P_{w1} - C_r\left(\Lambda(W) - \left[W\sum_{i=0}^{m-1}\delta_{iM} - \sum_{i=0}^{m-1}t_i\delta_{iM}\right]\right) - m\,C_{0p}\right\} + y_2\left\{P_s + P_{w2} - C_r\left(\Lambda(W) - \left[W\sum_{i=0}^{m-1}\delta_{iA} - \sum_{i=0}^{m-1}t_i\delta_{iA}\right]\right)\right\} \quad (14)$$

s.t.

$$P_a^* = y_1(R - P_s - P_{w1} - lnU_1(C)) \quad (15)$$

$$\left(C_{3r} + \frac{C_{3p}}{E[N_3]}\right)^* = y_1\left(\frac{1}{E[N_3]}\left(R - P_s - P_{w1} - lnU_{2(C)}\right)\right) \quad (16)$$

$$\left(C_{1r} + \frac{C_{2p}}{E[N_3]}\right)^* = y_2\left(\frac{1}{E[N_3]}\left(R - P_s - P_{w2} - lnU_3(C)\right)\right) \quad (17)$$

$$y_1 + y_2 = 1, y_1 \le z_1 + z_2, y_2 \le z_3 \quad (18-20)$$

<u>**Lower-level problem : Agent-Stackelberg Model**</u>

After having the values of P_{w1}, P_{w2}then this values become input values for the lower level problem. Thus, the agent model can be expressed as follows:

$$\max \rho_A(P_a, C_{3r}, C_{3p}, C_{1r}, C_{1p}) = z_1(P_a - C_rE[N_3] - ((k - m)C_{0p})) + z_2((C_{3r} - C_r)E[N_3] + \left(C_{3p} - (k-m)C_{0p}\right) + z_3\left((C_{1r} - C_r)E[N_3] + \left(C_{1p} - k\,C_{0p}\right)\right) \quad (21)$$

s.t.

$$z_1U_{1(C)} = \frac{1 - e^{-\gamma_1((R-P_s-P_{w1}-P_a))}}{\gamma_1} \quad (22)$$

$$z_2U_2(C) = U_2(C) = \frac{1 - e^{-\gamma_1((R-P_s-P_{w1}-C_{3p}-C_{3r}E[N_4]))}}{\gamma_1} \quad (23)$$

$$z_3U_3(C) = \frac{1 - e^{-\gamma_1((RL-P_s-P_w-C_{1p}-C_{1r}E[N_4]))}}{\gamma_1} \quad (24)$$

3.6 Solution Procedures

We consider the case of a convex bi-level problem, i.e. ρ_A and $h_iU_i(C)$ supposed to be convex functions in $P_a, C_{3r}, C_{3p}, C_{1r}, C_{1p}$ for all P_{w1}, P_{w2}. Thus, the agent model is convex. If we assume ρ_A and $h_iU_i(C)$ differentiable in $P_a, C_{3r}, C_{3p}, C_{1r}, C_{1p}$ for all P_{w1}, P_{w2}, then for fixed $P_{w1}, P_{w2}$and under an appropriate constraint qualification, the following KKT optimality conditions for problem (21) hold: $P_a, C_{3r}, C_{3p}, C_{1r}, C_{1p}$ is the solution for (21) if and only if there exist the Lagrange multiplier λ such that (Herskovits, et al., 2000):

$$\begin{cases} \nabla_{P_a,C_{3r},C_{3p},C_{1r},C_{1p}}\rho_A + \lambda\,.\,\nabla_{P_a,C_{3r},C_{3p},C_{1r},C_{1p}}h_i = 0 \\ \lambda\,.\,h_i\left(U_i(C)\right) = 0 \\ h_i\left(U_i(C)\right) \le 0, \lambda \ge 0 \end{cases} \quad (25)$$

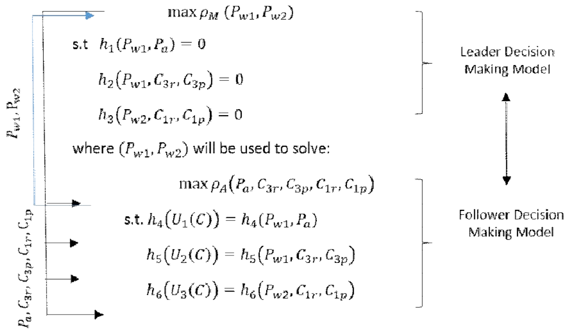

Fig.2. Bi-level optimization approach to the proposed models

Simulated annealing is used to obtain the best solutions. In each iteration, by solving the lower-level problem, the optimal reaction $(P_a, C_{3r}, C_{3p}, C_{1r}, C_{1p})^*$ is obtained and returned to the upper-level model. Also, we check the KKT condition on each iteration to ensure the global optimal solution. This procedure continues until an optimal/near-optimal solution reached for the lower-level problem and also upper-level problem. The optimal solution marked with two conditions: (i) reached the maximum iteration or (ii) the margin of error that has been reached. Flowchart showing the process of finding an optimal solution can be seen in Fig.3.Simulated annealing is performed using R Software.

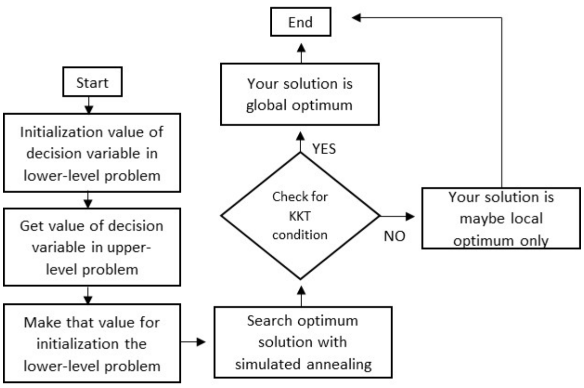

Fig.3. Bi-level optimization using KKT condition for finding solutions

IV. RESULTS AND DISCUSSION

In this section, we address numerical example aiming at illustrating the significant features of the models studied. We will also perform the managerial insights of three main parameters (reliability parameter, delta (reduction amount of the intensity function), and *W* (duration of the warranty).

4.1. Numerical example

The Stackelberg models produce the following optimal values for our decision variables based on equation (18) and (25):

$$\alpha = 3,\ P_{w1} = 21170,\ P_a = 1550,$$
$$\rho_{M1} = 23248.59,\ \rho_{A2} = 266,\ U_1(C) = 0$$

$$P_{w1} = 21170,\ C_{3r} = 700,\ C_{3p} = 800,$$
$$\rho_{M1} = 23248.59,\ \rho_{A3} = 102,\ U_2(C) = 17963$$

$$P_{w2} = 21080,\ C_{1r} = 7550,\ C_{1p} = 850,$$
$$\rho_{M2} = 23560.80,\ \rho_{A1} = 1126,\ U_3(C) = 18148$$

The result shows that the OEM, as the leader of the agent would choose option M2. The agent as the follower of the manufacturer and the leader of the customer, would choose option A1. And the customer has to choose option C3, which makes sense. In other words, the obtain sub-perfect-equilibrium (SPE), (M2, A1, C3) is tangible.

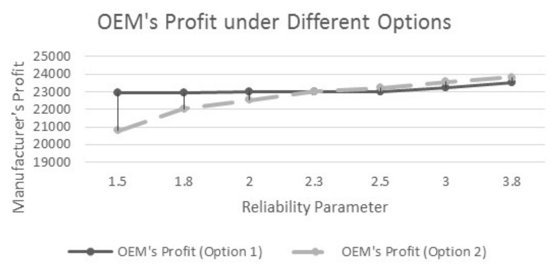

Fig.4. Domination of the OEM's options relative to reliability parameter.

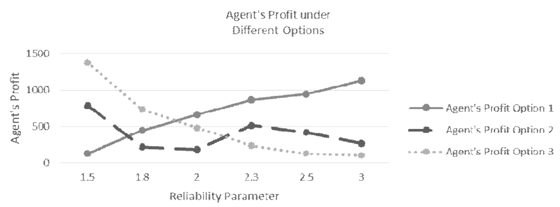

Fig.5. Domination of the Agent's options relative to reliability parameter.

4.2. Managerial Insights

In this section the effects of the parameter **reliability** on the choice of options are investigated. The effect of reliability parameter shows that (1) for more reliability equipment ($\alpha \geq 2.5$) the second option of the OEM is chosen. This because the game provides the second option of the OEM that is better. Therefore, OEM warranty price increases in line with increasing reliability. (2) Meanwhile, from the standpoint of the agent as a follower, the more reliable the engineering objects results in price maintenance packages that is the greatest benefits. This is possible because with the increase of reliability, expected damage to objects is also reduced, so that the agency simply act CM PM and little action. (3) As a result of taking the second option OEM (M2) and the first option agent (A1), the tangible solutions for the customer who is a follower of the agent is a third option (M3). However, what happens if the customer avoids the risk (with increased risk parameter), then the utility function of profit customer decreases (still under the influence of revenue, which should have been as a function of availability), interest is due to avoid the risk, the value of the utility function benefit the customer in every adjacent option. Thus, for the case of a major risk parameter and revenue of the customer is not a function of availability, the customer is free to choose the option that is tangible for him.

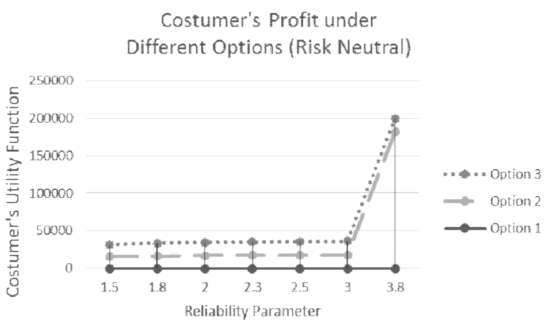

Fig.6. Domination of the Customer's options (risk neutral) relative to reliability parameter.

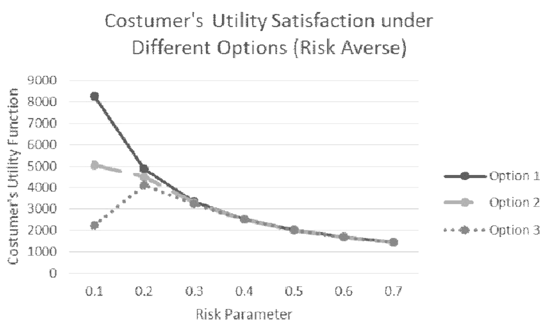

Fig.7. Domination of the Customer's options (risk averse) relative to reliability parameter.

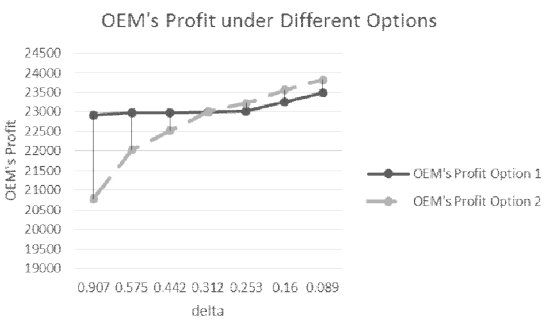

Fig.8. Domination of the OEM's options relative to delta.

CONCLUSIONS

In this paper, we have studied the optimal maintenance service contract involving three-parties (OEM, agent and customer) by using the Stackelberg game theory formulation. The optimal solution obtained by bi-level optimization approach, in which KKT condition is combined with simulated annealing. The major findings are as follows:

1. Asthe revenue is not a function of availability, then the increased in the reliability does not contribute to the increased in the profit of OEM for option M2, the profit of SA for option A1,and the benefit of the consumer for option C3 (or M2 and A1)
2. Bi-level optimization approach is capable of solving the decision problemsinvolving three parties modelled by a Stackelberg game theory, and we obtain global optimum solution which complies with the KKT conditions.

There are much works in extending the present work. One topic is that considering the revenue which is a function of availability, and penalty and incentive factors. Another topic would be the case where the EOM offers some extended warranties. And the approach to obtain the optimal solutions - One can improve simulated annealing and compared with other metaheuristic methods to get better results.

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