A Game-Theoretic Model for Outsourcing Maintenance Services

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SUMMARY & CONCLUSIONS

Proactive maintenance improves the operational availability of a system and increases the owner's profit. To create more economic value along this direction, it is popular to outsource maintenance services to a service agent. However, due to various uncertainties in equipment failures and spare part logistics, making a service agreement between the owner and the service agent can be quite complex. In this paper, a game-theoretic cooperative model is presented to facilitate contract negotiation in such a joint decision-making process. In particular, the owner determines the time for preventive replacement and the service agent makes up a plan on ordering a spare part such that their overall profit is maximized. To sign a long-term contract, the two players need to share the overall profit in a fair manner based on Shapley values that satisfy certain axioms of fairness. Numerical examples are provided to illustrate the solution methodology and to highlight the managerial implications in reliability and maintenance management.

1 INTRODUCTION

It is important to ensure the operational availability of critical equipment subject to random failure. Because of obvious economic advantages, determinations of optimum policies for preventive replacement and spare parts ordering have been extensively studied [1]. For preventive replacement optimization, a popular objective is to minimize the expected cost per unit of time based on renewal reward theorem [2] [7]. Regarding spare part ordering, Osaki [3] studied an ordering policy for a part with constant lead time. Park and Park [4] determined the optimum spare ordering policy and maintenance policy considering variable lead time. Thomas and Osaki [5] discussed a generalized spare ordering policy with constant and variable lead time. Instead of studying maintenance and spare part ordering separately, Armstrong and Atkins [6] investigated joint optimization of maintenance and inventory policies.

It is worth pointing out that most of the related studies have assumed that maintenance is performed internally by the owner of the equipment. However, in today's business environment companies would like to focus more on their fields of specialty (core competencies) and thus are often willing to outsource regular maintenance to service agents. In the short term, the advantage of outsourcing service is cost reduction. In practice, an agent, specializing in a technical area, can provide professional maintenance service at a low cost. Besides, elimination of spare part inventory and a maintenance team can significantly save the operational cost for the company. Moreover, outsourcing maintenance service can help companies reduce their risks considerably and provide an improved service level to their customers as a result of the efficient maintenance services provided by their service agents [8].

Obviously, both the company and the service agent prefer to make more profits by signing a service contract that is the most favorable. However, a participant's best result cannot be achieved without considering the possible decision to be made by the counterpart. Game theory is the most popular means of modeling the conflict between two or more decision makers [9]. Depending on the behavior of decision makers, different game-theoretic methods, such as leader-follower, non-cooperative and cooperative games can be used. Ashgarizadeh and Murthy [10] assumed an agent as the leader deciding on the price structure and the number of customers to serve while each customer, as a follower, owning a piece of repairable equipment with constant failure rate, decides on three available contracting options. A similar problem was considered in [11] where each agent is also assumed to decide on the number of service channels for serving several customers simultaneously. Moreover, two leader-follower models were developed in [12] for non-repairable equipment. In the first model the agent always carries a spare part in the inventory while in the second model the agent decides on the optimum ordering time for a spare part with zero lead time.

Other than leader-follower games, the customer and the agent can also determine their strategies simultaneously. For example, Jackson and Pascual [13] considered a non-cooperative game for equipment with a linear failure rate. In most cases, the solutions to non-cooperative games can be improved for both players if they cooperate by giving up their interdependence. When

players cooperate they try to maximize their overall profit and share it between themselves. There are different views on distributing the total profit which result in different solution concepts. Tarakci et al. [14] studied three long-term contracts that motivate the agent to coordinate with the customer without considering the fairness in sharing the profit.

Shapley value is one of the most popular solutions for sharing the coalition's overall profit in a fairly manner. In this paper, we consider a cooperative game for an agent and a customer sharing their profit based on Shapley values for a case with constant lead time. It is worth mentioning that in [15] the authors considered uniformly distributed lead time.

This paper is structured as follows. In Section 2, problem description is presented. Section 3 provides the model formulation. A brief review of basic concepts of cooperative game and Shapley values are explained in Section 4. Numerical examples are presented in Section 5 to illustrate the solution methodology. Finally, Section 6 concludes the paper and outlines our future work.

2 PROBLEM DESCRIPTION

The owner of a piece of equipment makes revenue R per unit of time when the equipment is in operation, and no revenue is generated when it is failed. The equipment's lifetime X has an increasing failure rate with cumulative distribution function $F(x)$, probability density function $f(x) = dF(x)/dx$, and reliability function $\bar{F}(x) = 1 - F(x)$. The owner outsources replacement service to a service agent. If they come to an agreement, the service agent will be responsible for performing failure replacement and preventive replacement at equipment age T_R determined by the owner. As a customer, the owner pays the service agent P_p and P_f, for which $P_p \le P_f$, for each preventive and failure replacement, respectively. For the agent, the actual cost of performing failure replacement is C_f, which is higher than the cost of preventive replacement, C_p.

The service agent orders a spare part after a constant time T_0 following the latest replacement. The part will be received at $T_0 + L$ after a constant lead time L. The service agent can hold at most one part in the inventory, and it is assumed that $T_0 \ge 0$ to make sure that at the time of arrival of a part there are no other spares in stock. Note that a generalized ordering policy where $T_0 \ge -L$, can be seen in [5].

When the unit currently being used must be replaced, the agent does an immediate and perfect replacement if a spare is on-hand; otherwise delayed replacement is performed at the time when the ordered spare arrives. In the case of delayed replacement, the agent has to compensate the customer for the downtime loss, which is R per unit of time. The agent and the customer are willing to cooperate

and agree on a fair profit to sign a long-term contract. The decision variable for the customer is the preventive replacement age T_R, and the part ordering time T_0 is the decision variable for the agent. We assume that $T_0 + L \le T_R$. In terms of game theory, the customer and the agent are called two players and the decision variables T_R and T_0 are called the players' strategies.

Table 1 gives the notation used in this paper.

Notation	
C_i	Inventory cost per unit time
R	Revenue per unit time
C_f	Cost of failure replacement
C_p	Cost of preventive replacement
P_f	Charge of failure replacement
P_p	Charge of preventive replacement
L	Lead time
X, x	Random and actual failure time of equipment
T_R	Preventive replacement age
T_0	Time to place an order

Table 1 – Nomenclature

3 MODEL FORMULATIONS

The expected profits per unit of time can be used as the payoff functions of the customer and the agent when the two parties sign a long-term service contract. Defining a cycle as the time period starting from the installation of a new part to the time of replacement, the expected profit per unit of time can be calculated as the ratio between the expected cycle profit and the expected cycle length based on renewal reward theorem [2]. The payoff functions for the players are derived next.

For $T_0 + L \le T_R$, there are three possibilities in each cycle. The first possibility is the one where the equipment fails before the agent receives the spare item, i.e., $X \le T_0 + L \le T_R$. In this case, the agent delays the required failure replacement until the spare part is received at $T_0 + L$. Therefore, the cycle length is $T_0 + L$ and the customer's profit is $R(T_0 + L) - P_f$. Clearly, the agent's profit can be expressed as $P_f - C_f - R(T_0 + L - X)$ since the agent compensates the customer for the loss of revenue for the delay period $(T_0 + L - X)$. It is assumed that the shortage cost is equal to R.

The second possibility occurs when the failure happens after the arrival of the ordered spare and before the scheduled replacement time, i.e., $T_0 + L < X \le T_R$. The agent does failure replacement instantaneously, so the cycle length is X and the profit for the customer is $RX - P_f$ and for the agent is $P_f - C_f - (X - T_0 - L)C_i$ which includes

the holding cost.

The last possibility is that the actual lifetime of the equipment is longer than the scheduled replacement time, i.e., $T_0 + L \leq T_R < X$. In this case, the scheduled preventive replacement is performed by the agent at T_R, so the cycle length is T_R and the profit for the customer is $RT_R - P_p$ and the profit for the agent is $P_p - C_p - (T_R - T_0 - L)C_i$ where the inventory holding cost is also considered.

3.1 *Customer's Payoff Function*

Considering all the three possibilities, the customer's expected profit per cycle can be expressed as
and the expected cycle length is

$$EPC = RT_R - R \int_{T_0+L}^{T_R} F(x)dx - P_f F(T_R) - P_p \bar{F}(T_R)$$

$$ECL = \int_0^{T_0+L} (T_0+L)f(x)dx + \int_{T_0+L}^{T_R} xf(x)dx + \int_{T_R}^{\infty} T_R f(x)dx$$

$$= T_R - \int_{T_0+L}^{T_R} F(x)dx$$

$$(1)$$

Therefore, the long-run profit per time unit for the customer can be expressed as

$$JC(T_R, T_0) = \frac{EPC}{ECL} = R - \frac{P_f F(T_R) + P_p \bar{F}(T_R)}{T_R - \int_{T_0+L}^{T_R} F(x)dx} \quad (2)$$

3.2 *Agent's Payoff Function*

Similarly, the expected cycle profit of the agent is the expectation of the three profits mentioned above which can be expressed as

$$EPA = (P_f - C_f)F(T_R) + (P_p - C_p)\bar{F}(T_R)$$

$$-R \int_0^{T_0+L} F(x)dx + C_i \int_{T_0+L}^{T_R} F(x)dx - (T_R - T_0 - L)C_i$$

As a result, the long-run profit per time unit for the agent is:

$$JA(T_R, T_0) = \frac{EPA}{ECL} \quad (3)$$

Notice that the payoff function of the customer (2) depends on the decision variable T_0 of the agent, so the optimal T_R values are a function of T_0, i.e., $T_R = \varphi(T_0)$. Similarly, the payoff function of the agent (3) depends on the decision variable T_R of the customer, so the optimal solution of T_0 is a function of T_R, i.e., $T_0 = \psi(T_R)$. In game theory, φ and ψ are called the response functions of the players.

4 COOPERATIVE GAME

A model with two decision makers can be considered by different concepts depending on the behavior of the decision makers. If they decide independently, Nash equilibrium should be used where the Nash equilibrium can be obtained as the result of the simultaneous response functions equations: $T_R = \varphi(T_0)$ and $T_0 = \psi(T_R)$. Nash equilibria are not Pareto optimal in most games, like in the case of the prisoners' dilemma. That means the payoffs of both players can be improved simultaneously from the equilibrium. If the players give up their interdependence in making decisions and actually cooperate, their profit would be increased considerably and cooperating solution with Shapley value can be considered. In this section, a brief review of basic concepts for cooperative game [9] is presented to help practitioners understand the use of these ideas in maintenance outsourcing.

When players cooperate, they try to maximize their overall profit and share it fairly between them. There are different views of fair profit distribution, which lead to different solution concepts. The most popular solution for sharing the coalition's overall profit is given by Shapley values which measure the value of each player in a game based on the characteristic function of the game which can be described as follows.

Let $N = \{1, \ldots, n\}$ be the set of players in an n-person game. Any subset $S \subseteq N$ is called a coalition. When a group is cooperating, players outside the coalition try to punish them while the players in the coalition try to maximize their overall profit. The guaranteed total profit that the coalition can achieve regardless of the actions of other players is given by

$$v(S) = \max_S \min_{N-S} \sum_{i \in S} \varphi_i$$

which is called characteristic function at S, and φ_i is the payoff function of player i. In the two special cases of the empty coalition where none of the players cooperate and the grand coalition where all the players cooperate, the characteristic functions are $v(\varnothing) = 0$ and $v(N) = max \sum_{i=1}^{n} \varphi_i$, respectively. The question is how to fairly share the total profit among the players. For this purpose, Shapley value can be used which can be explained either mathematically or heuristically [9].

Based on Shapley Value, a fair amount to give to each player is the expectation of his marginal contribution to all possible coalitions of the game. For an n-player game, there are 2^n possible coalitions of the players. Suppose player i is the last person joining the coalition S. In this case the marginal contribution of player i after joining the coalition S can be defined as $d_i(S) = v(S) - v(S \setminus \{i\})$. Then, the expectation of the marginal contribution of player i can be calculated by

$$y_i = \sum_{S \subseteq N} \frac{(s-1)!(n-s)!}{n!} d_i(S)$$

where $s=|S|$. The reason is that there are $\binom{n}{s}$ possibilities to choose s players from n players, so the probability that a particular s-element coalition is chosen is $1/\binom{n}{s}$. However, as player i can be in any of the s positions the probability that a particular coalition is selected with player i being in the last position is $1/\left(s\binom{n}{s}\right) = (s-1)!(n-s)!/n!$. As a result, $d_i(S)$ is multiplied by the probability that player i is the last person joining the coalition, and as $d_i(S)$ is his corresponding contribution, x_i is the expected value of his contribution.

As an example, the Shapley values for the agent and customer can be calculated easily as follows. There are four possible coalitions for this two-person game: $\{C\}$, $\{A\}$, $\{C,A\}$ and $\{\varnothing\}$, where A represents the agent and C represents the customer. There are two coalitions with the agent as a member, i.e., $\{A\}$ and $\{C,A\}$. The marginal contribution of the agent to each of these coalitions are $v(\{A\}) - v(\varnothing)$ and $v(\{C,A\}) - v(\{C\})$, respectively, each with probability of 1/2. The same process can be applied for the customer too. Calculating the expectation of the marginal contribution of the customer, y_C, and the agent, y_A, the corresponding Shapley Values are

$$y_C = \frac{v(\{C\}) + v(\{C,A\}) - v(\{A\})}{2} \tag{4}$$

$$y_A = \frac{v(\{A\}) + v(\{C,A\}) - v(\{C\})}{2} \tag{5}$$

where $v(\{C\}) = \max_{T_R} \min_{T_0} JC$, $v(\{A\}) = \max_{T_0} \min_{T_R} JA$ and $v(\{C,A\}) = \max_{T_R, T_0} JC + JA$ are characteristic functions for different coalitions.

The actual decisions the customer and the agent make are T_R^* and T_0^* which maximize the total profit, i.e., $v(\{C,A\})$ and they make a deal to share this profit based on Shapley values, i.e., (4) and (5). It should be noted that the actual payoffs, $JC(T_R^*, T_0^*)$ and $JA(T_R^*, T_0^*)$, the players get directly (by substituting the optimum decisions into (2) and (3)) after the game is played are not usually equal to Shapley values related to the fair profit the players dealt with in the first step. In order to ensure the fair profit to the players, they should compensate each other where these compensations are called side payment which requires a certain level of trust between the players. This would be clarified in the next section.

5 NUMERICAL EXAMPLES

In this section, numerical examples are presented to illustrate the corporative game in service contract negotiation and the effects of parameter variations on the optimal strategies of the two players and their Shapley Values.

The distribution for time to failure is assumed to be the Weibull with $f(x) = \beta/\alpha(x/\alpha)^{\beta-1} e^{-(x/\alpha)^\beta}$. The parameters assumed for the problem setting are $C_i = 10$, $R = 30$, $C_f = 300$, $C_p = 100$, $P_f = 800$, $P_p = 600$, $L = 10$, $\alpha = 40$, $\beta = 3$. The optimum solutions of cooperation for this set of parameters are $v(\{C\}) = 7.82$, $v(\{A\}) = 9.04$ and $v(\{C,A\}) = 22.92$, and the optimum strategies for the customer and the agent are $T_R^* = 20.3$ and $T_0^* = 10.32$, respectively. The customer and the agent make a deal to play these optimum strategies and gain $y_C = 10.85$ and $y_A = 12.07$ per unit of time or 47.33% and 52.67% of the total profit, respectively (based on (4) & (5)). It should be noted that the profit the players gain directly after playing this game is $JC(T_R^*, T_0^*) = 1.18$ and $JA(T_R^*, T_0^*) = 21.74$. In this decision-making process, the players should compensate each other, which means that the agent should keep $y_A = 12.07$ and pay the rest of his revenue to the customer. One can see that this game involves side payments and is based on full trust between the two players as the agent might resist compensating the customer.

The resulting optimal solutions are compared for different values of the scale parameters $\alpha \in \{30, 40, 50, 70\}$ and shape parameters $\beta \in \{2, 3, 5, 7\}$ of the failure time distribution, lead time $L \in \{10, 35, 40, 45\}$, unit holding cost per time unit $C_i \in \{0, 10, 35, 70\}$, failure replacement cost $C_f \in \{200, 300, 500, 700\}$, preventive replacement cost $C_p \in \{50, 100, 200, 250\}$, failure replacement charge $P_f \in \{700, 800, 900, 1000\}$, and preventive replacement charge $P_p \in \{200, 300, 600, 700\}$. In the following tables, columns y_C % show the customer's percent share of total profit and columns y_A% are the corresponding values for the agent based on Shapley values.

α	$v(\{C\})$	$v(\{A\})$	$v(\{C,A\})$	y_C %	y_A%
30	0.5	13.55	20.90	18.75	81.25
40	7.82	9.04	22.92	47.33	52.67
50	12.24	6.34	24.15	62.19	37.81
70	17.31	3.27	25.60	77.42	22.58

Table 2 – Effect of Scale Parameter on Shapley Values

β	$v(\{C\})$	$v(\{A\})$	$v(\{C,A\})$	y_C %	y_A%
2	7.39	7.66	20.50	49.31	50.69
3	7.82	9.04	22.92	47.33	52.67
5	9.16	10.26	24.82	47.78	52.22
7	10.17	10.83	25.60	48.71	52.19

Table 3 – Effect of Shape Parameter on Shapley Values

L	$v(\{C\})$	$v(\{A\})$	$v(\{C,A\})$	y_C %	y_A%
10	7.82	9.04	22.92	47.33	52.67
35	10.57	7.31	20.15	58.06	41.94
40	11.89	5.40	18.56	67.45	32.55
45	13.29	3.09	16.94	80.10	19.90

Table 4 – Effect of Lead Time on Shapley Values

Tables 2 reveals that the equipment with a higher scale parameter (of Weibull distribution) results in a bigger share of profit to its owner which sounds logically reasonable since an increase in the scale parameter increases the mean time to failure of the equipment which results in less profit for the agent but a higher profit for the customer. On the other hand, Table 3 shows that a higher shape parameter of the equipment makes the agent's share of profit higher because of higher failure probability of the equipment.

Table 4 shows that the order lead time negatively affects the agent's profit but positively affects the share of the customer, and such effects are quite sensitive to the lead time.

C_i	$v(\{C\})$	$v(\{A\})$	$v(\{C,A\})$	y_C %	y_A%
0	7.82	13.95	23.88	37.14	62.86
10	7.82	9.04	22.92	47.33	52.67
35	7.82	3.86	22.92	58.63	41.37
70	7.82	0.84	22.92	65.22	34.78

Table 5 – Effect of Holding Cost on Shapley Values

C_f	$v(\{C\})$	$v(\{A\})$	$v(\{C,A\})$	y_C %	y_A%
200	7.82	11.74	23.56	41.68	58.32
300	7.82	9.04	22.92	47.33	52.67
500	7.82	3.65	21.84	40.48	59.52
700	7.82	0	20.95	68.63	31.37

Table 6 – Effect of Failure Cost on Shapley Values

C_p	$v(\{C\})$	$v(\{A\})$	$v(\{C,A\})$	y_C %	y_A%
50	7.82	9.04	25.43	47.58	52.42
100	7.82	9.04	22.92	47.33	52.67
200	7.82	9.03	19.49	46.89	53.11
250	7.82	8.95	18.27	46.90	53.10

Table 7 – Effect of Preventive Cost on Shapley Values

The second columns of Tables 5 – 7 show that the customer's characteristic function value is not a function of C_i, C_f and C_p. The agent's share of the total profit decreases as these cost elements increase.

P_f	$v(\{C\})$	$v(\{A\})$	$v(\{C,A\})$	y_C %	y_A%
700	10.42	6.34	22.92	58.90	41.10
800	7.82	9.04	22.92	47.33	52.67
900	5.60	11.74	22.92	36.60	63.40
1000	3.68	14.32	22.92	26.78	73.22

Table 8 – Effect of Failure Charge on Shapley Values

P_p	$v(\{C\})$	$v(\{A\})$	$v(\{C,A\})$	y_C %	y_A%
200	16.20	5.53	22.92	73.25	26.75
300	12.79	7.56	22.92	61.38	38.62
600	7.82	9.04	22.92	47.33	52.67
700	7.61	9.04	22.92	46.85	53.15

Table 9 – Effect of Preventive Charge on Shapley Values

Moreover, it can be easily seen from Tables 8 and 9 that $v(\{C,A\})$ is not a function of P_f and P_p since those terms with prices cancel each other in the total profit. Besides, the payoff function of the agent is an increasing function of prices and this can cause unboundedness to the problem. For these reasons, we do not consider prices as decision variables and assume the prices as parameters determined by the market.

6 CONCLUSIONS

In this paper, the problem of outsourcing preventive and failure replacements of critical equipment to a service agent has been discussed, where the owner of the equipment and the service agent (players) intend to cooperate to gain more profits. They agree on a fair profit for both players based on Shapley values in order to sign a long-term contract. Although this cooperation generates a big profit, it involves side payments. This means that the players should compensate each other after the game is played which requires complete trust between the players as one player might resist compensation. When this is not the case, conflict resolution methods, such as Nash Bargaining Solution, can be used, in which players jointly determine and agree on the optimal strategies but no further side payments are involved and the direct profit each player receives after the game is played is his/her actual profit too.

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