The Integrated Supply Chain of After-sales Services Model: A Multi-objective Scatter Search Optimization Approach

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Abstract

In recent decades, high profits of extended warranty have led third-party firms considering it as a lucrative after-sales service. However, customers' division in terms of risk aversion and effect of offering extended warranty on manufacturers' basic warranty should be investigated through adjusting such services. Risk-averse customers welcome extended warranty, while the customers without taking on risk may remain at the level of basic warranty. In this paper, a multi-objective integer nonlinear programming model is presented for integrating the supply chain of after-sales services. In the suggested model, firstly the strategies used by the manufacturers in the basic warranty period and the third party's policy during the extended warranty period, including the development of a new imperfect maintenance approach, are regulated. The effects of these strategies on the desirability of customers with different levels of risk-taking are then analyzed. In order to optimize the model, the scatter search based approach was introduced for extracting set of non-dominated solutions. The results indicated that increasing level of customers’ risk-taking convinces manufacturers to diminish the basic warranty period and the third party can apply less costly preventive maintenance.


1. INTRODUCTION

In after-sales services, product warranty refers to a contract between manufacturer and customer which shows the manufacturer’s responsibility for repairing/replacing services or paying customer compensation due to the existence of a defective product within a specified time period called “warranty period” [1]. In addition to basic warranty (BW) that is issued in the form of a bundle with the product, extended warranty (EW) is proposed for products with a long useful life. EW is usually suggested to customers at the end of BW; therefore, the third-party (3P) companies such as insurance ones are interested in offering it. Extended warranty usually possesses high profit margins. For example, purchasing EW ranges from 30% for products such as cars to 75% for electronic devices and their applications [2].

Generally, there are two classifications in relation to basic and extended warranty: (1) Studies which consider EW independent from BW; (2) Studies which consider EW with regard to the effect of BW and in the form of a supply chain of after-sales services. In the first group, EW is investigated only from the customer, manufacturer, or the third party’s viewpoints [3-6]. However, from customers’ viewpoints, extended warranty can be complementary and sometimes replace basic warranty. As a consequence, strategies of EW periods affect the manufacturers. In addition, the strategies adopted by the manufacturer during the BW period are effective on EW policies of the third party; hence, the second group of studies is considered.

Jiang and Zhang [7] investigated the effect of EW policies of a 3P on warranty strategies offered by a manufacturer. The results illustrated that for the manufacturer displaying product quality to customers at the time of existence of EW is more possible compared to its absence. Heese [8] indicated that although increasing BW period for a product causes the establishment of its position against competitors’...
products, customers of the product are less interested in EW. This issue is due to the overlap of BW with EW. Esmaeili et al. [9] used a game theory approach to model the contracts between the third party, manufacturer and costumer in non-cooperative and semi-cooperative states.

Since warranty service costs directly affect the provider’s profit, studies [10-17] applied maintenance strategies alongside BW/EW policies to reduce incurred costs. Although the conducted studies in the second group investigate the concurrent effects of BW and EW on each other, they mostly assume that customers have the same interests to the offered warranty. However, in the real world, degrees of customers’ risk-taking are different; consequently, negligence of after-sales service providers to this issue, particularly EW providers, can not only increase costs of warranty periods, but also involve the risk of customers’ unwillingness to the offered warranty.

In this paper, a multi-objective integer nonlinear programming (MOINLP) model is presented for integrating the supply chain of after-sales services with considering the manufacturer, third party and customer’s viewpoints. In the proposed model, BW is supported by one manufacturer and EW is offered by a 3P. Moreover, customers have different degrees of risk-taking and policies adopted by the manufacturer and 3P affect their desirability. Since EW is carried out after the end of BW, a new imperfect maintenance strategy based on virtual age approach will be developed from the third party’s viewpoint. As the proposed model is a MOINPL, obtaining optimal solutions for large scale of such problems is practically impossible. So, a multi-objective scatter search approach is developed for extracting a set of non-dominated solutions. According to our knowledge, this is for the first time that an integrated after-sales services model is developed to optimize policies of warranty and extended warranty periods upon maintenance strategies and customers’ desirability.

In the following, the problem definition is presented in Section 2. In Section 3, the model components including manufacturer, 3P and customer’s perspectives are discussed. The integrated supply chain of after-sales services model is introduced in Section 4. The proposed solution approach is presented in Section 5. The numerical examples are discussed in Section 6. Finally, concluding remarks and suggestions for further research are discussed in Section 7.

2. PROBLEM DEFINITION

Consider a repairable product that faces failures over time and as a result of deterioration process. Suppose that the random variable of $T$ shows failure process.

$0f(t)$ and $F(t)$ are respectively the probability distribution function and the cumulative distribution function of failure process. Accordingly, the hazard rate function ($h(t)$) will be calculated as follows:

$$h(t) = \frac{f(t)}{1 - F(t)}$$  \hspace{1cm} (1)

$h(t)$ is an increasing function that enhances over time due to deterioration process and finally lead to product breakdown. The product is sold by a manufacturer to a set of customers as a bundle with non-renewable basic warranty for a period of time BW. After the basic warranty is expired, a non-renewable extended warranty is offered to customers by a third party during the EW. Since the degree of risk-taking is different among customers, there is no same willingness to pay to the proposed extended warranty.

Suppose, random variable of $r_{i}$ represents the $i$th customer’s risk taking, that is defined in the range of $[0, R]$ and has the $g(r_{i})$ probability function. In these circumstances, $r_{i} = R$ shows a customer is highly risk-averse and $r_{i} = 0$ indicates a risky customer. The more a customer is risk-taking, the less he/she uses the extended warranty of products [7] and the product failure has less negative effect on him/her [6]. In addition, the duration of the basic and extended warranty for customers with different degrees of risk taking, does not make equal desirability. As a result, third party and the manufacturer should set the warranty policy with the aim of controlling its associated costs along with maximizing the customers’ satisfaction.

3. COMPONENTS OF THE MODEL

This section gives the model components, including the customer's perspective, the opinions of third-party and the manufacturer, in addition to provide a base for introducing an integrated supply chain model of after-sales services.

3.1. Manufacturer Perspective

Manufacturer, only performs minimal corrective maintenance (CM) during the basic warranty period and does not apply any preventive maintenance (PM) policy. In this regard, the average number of CM actions during the basic warranty for one product will be in the form of Equation (2):

$$N_{BW} = \int_{0}^{BW} h(t)dt$$  \hspace{1cm} (2)

$N_{BW}$ is a function of the basic warranty period. If $C_{CM}$ defines cost of carrying out one CM by the manufacturer, then total cost of basic warranty period for a product from the manufacturer perspective can be obtained as follows:
The extended warranty period is sent for inspection and the product returns to the condition of "as bad as new". At the time of PM inspection deterioration process is greater than or equal to \( \gamma^\text{upper} \), in a way that \( \delta(m) = 1 \) transfers the product to “as bad as old” condition and \( \delta(m) = 0 \) transfers the product to “as good as new” condition.

According to Equation (6), after failure rate at the moment \( \tau_3 \) reduced to level \( \gamma(\tau_3) \), corresponding virtual age of this level is determined by function \( h^{-1}(\cdot) \). After the \( p \)th PM, the virtual age \( (\tau_p) \) and the failure rate are calculated as follows:

\[
h(\tau_p) = h(\tau_{p-1} + \Delta) \quad p = 2, ..., n, \tag{8}
\]

\[
\tau_p = h^{-1}(\gamma(\tau_{p-1} + \Delta)) \quad p = 2, ..., n. \tag{9}
\]

As is evident in relations (8) and (9), the failure rate after applying the \( p \)th preventive maintenance is a fraction of failure rate before that. The virtual age and the failure rate in the range of \( \tau_p \leq t < \tau_{p+1} \) are as follows:

\[
v(t) = \tau_p + (t - \tau_p), \quad \tau_p \leq t < \tau_{p+1} \quad p = 2, ..., n, \tag{10}
\]

\[
h(\tau_p) = h(\tau_{p} + (t - \tau_p)), \quad \tau_p \leq t < \tau_{p+1} \quad p = 2, ..., n. \tag{11}
\]
2, ..., n − 1

Finally, Equations (12) and (13) show the values of the virtual age and the failure rate in the range of τ_n ≤ t ≤ EW.

\[ v(t) = v_n + (t - τ_n), \quad τ_n ≤ t ≤ EW \]  \tag{12}

\[ h(v(t)) = h(v_n + (t - τ_n)), \quad τ_n ≤ t ≤ EW \]  \tag{13}

Since the occurred failures in the product are rectified minimally and with a negligible time, the expected number of failures in each interval can be obtained by integrating the hazard rate function during that interval. As a result, the expected number of failures over an extended warranty period (N_{EW}) is obtained as:

\[ N_{EW} = \int_{EW}^{\infty} h(v(t))dt. \]

So, we have the following equation (14):

\[ N_{EW} = \int_{EW}^{\infty} h(v(t))dt = \int_{BW}^{\infty} h(v(BW)) + (t - BW)dt + \sum_{p=0}^{n-1} \int_{p}^{\infty} h(v(t))dt \]

\[ + \int_{0}^{\infty} h(v + (t - τ_n))dt \]  \tag{14}

Suppose \( C_{PM} \) is defined as the total cost of doing CM on a product during the extended warranty. Then the expected CM costs for a customer’s product during extended warranty period is obtained as:

\[ ECM_{EW}(\Delta, m) = \sum_{p=1}^{n} C_{PM} X_p \]  \tag{15}

In Equation (16), \( y_p \) is a binary variable. If the value of a deterioration process at \( p \)th PM action is placed between upper and lower allowable limit, it will be one and otherwise it will be zero, that is:

\[ y_p = \begin{cases} 1 & \text{if } \gamma_{lower} < h(v_{p-1} + \Delta) < \gamma_{upper} \\ 0 & \text{otherwise} \end{cases} \]  \tag{17}

1, 2, ..., n.

In Equation (17), the cost of PM actions (i.e., \( C_{PM} \)) depends on the level of chosen maintenance (m). The average number of required spare parts during the extended warranty period is obtained as follows:

\[ E_{SPW}(\Delta, m) = \sum_{p=1}^{n} X_p \]  \tag{18}

In Equation (18), \( x_p \) is the binary variable and if the deterioration process at time of \( p \)th PM inspection is equal to or greater than upper allowed limit, it will be one and otherwise it will be zero, that is:

\[ x_p = \begin{cases} 1 & \text{if } h(v_{p-1} + \Delta) ≥ \gamma_{upper} \\ 0 & \text{otherwise} \end{cases} \]  \tag{19}

\[ p = 1, 2, ..., n. \]

As it is evident in Equations (15), (16) and (18), the values of ECM_{EW} and EPM_{EW} and ES_{EW} are a function of maintenance policies made by the third party during the extended warranty period, including the values of the distance between two consecutive PM (\( \Delta \)) and the applied PM level (m). The total cost of the third party among extended warranty period (TC_{3P}) is as follows:

\[ TC_{3P} = ECM_{EW}(\Delta, m) + EPM_{EW}(\Delta, m) + ES_{EW}(\Delta, m) \]  \tag{20}

3. 3. Customers Perspective

As mentioned before, the rate of risk-taking of customers is shown by the random variable of \( r \). For the \( i \)th customer with \( r_i \) value of risk taking, the function of \( \psi(EW|r_i) \) indicates the desirability of extended warranty, which is defined in the following:

\[ \psi(EW|r_i) = x_i \theta \exp{\theta(r_i - \theta)} \]  \tag{21}

In Equation (21), values of \( x, \theta \) and \( \theta \) are the scale, shape and center parameters. According to Equation (21), the \( i \)th customer with the risk-taking degree of \( r_i \in [0, \theta] \) is assumed risk-taker. In this case, by increasing the length of the extended warranty period, his desirability decreases. For values of \( r_i \in [\theta, R] \), the \( i \)th customer is assumed risk averse. In this case, by increasing the warranty period, his desirability value increases. Based on the customer desirability, the expected value of the \( i \)th customer’s desirability of the proposed extended warranty, can be concluded as follows:

\[ \psi(EW) = \int_{0}^{R} \psi(EW|r) g(r_i) dr = \int_{0}^{R} x_i \theta \exp{\theta(r_i - \theta)} g(r_i) dr \]  \tag{22}

The probability function of risk-taking (i.e., \( g(r) \)) is triangular distribution and is defined as Equation (23):

\[ g(r) = \begin{cases} \frac{2r}{\theta^2} & 0 ≤ r ≤ \theta \\ \frac{2R - r}{\theta^2} & \theta ≤ r ≤ R \end{cases} \]  \tag{23}

In Equation (23), customers are risk-taking in the \( r \in [0, \theta] \) and are risk-averse in the \( r \in [\theta, R] \). By substituting Equation (23) in (22), we have:

\[ \psi(EW) = \int_{0}^{R} x_i \theta \exp{\theta(r_i - \theta)} g(r_i) dr = \int_{0}^{\theta} \frac{2\theta}{R^2} x_i \theta \exp{\theta(r_i - \theta)} dr + \int_{\theta}^{R} \frac{2\theta}{R^2} x_i \theta \exp{\theta(r_i - \theta)} dr = \frac{2\theta}{R^2} x_i \theta \exp{\theta(r_i - \theta)} \exp{\theta(r_i - \theta)} + \int_{0}^{\theta} \frac{2\theta}{R^2} x_i \theta \exp{\theta(r_i - \theta)} dr + \int_{\theta}^{R} \frac{2\theta}{R^2} x_i \theta \exp{\theta(r_i - \theta)} \exp{\theta(r_i - \theta)} \]  \tag{24}
Equation (24) shows the expected customer’s desirability from offered extended warranty to the length of EW. Using Equation (25), the customer’s desirability function of Extended Warranty converts in the interval [0,1]. In Equation (25) ψ_{min} and ψ_{max} are the minimum and maximum values of customer’s desirability from the offered extended warranty. In this regard, if u = 1, the shape of d(EW) function is linear. If u < 1, is concave and if u > 1, is convex [18].

\[
d(EW) = \begin{cases} 
0 & \text{if } \psi(EW) < \psi_{min}
\end{cases} \quad (25)
\]

Since the basic warranty is presented as a bundle with the product, it is assumed that the customers, either risk-taking or risk averse, will have a higher desirability with the longer basic warranty. As a result, function of customer’s desirability from basic warranty (d(BW)) is defined as follows (q parameter is similar to u parameter in Equation (25)).

\[
d(BW) = \begin{cases} 
0 & \text{if } BW < BW_{min}
\end{cases} \quad (26)
\]

In addition to the extended warranty period, the number of failures occurred during the basic warranty and extended warranty period also affect customer satisfaction. In such conditions, the occurrence of product failure is associated with more dissatisfaction with increasing degree of risk aversion.

Suppose that π(N|r_i) represents the ith customer satisfaction with a degree of r_i for risk-taking, at the time of existence N failures during the warranty period. Then we have:

\[
π(N|r_i) = \frac{a}{(1+N)^t} \quad (27)
\]

The expected customer’s satisfaction when there are N failures in a product will be obtained as follows:

\[
d(N) = \int_0^N π(N|r_i) g(r_i) \, dr_i = \int_0^\theta \frac{2r_i^2}{R(\theta)(1+N)^t} \, dr_i + \int_\theta^R \frac{2r_i}{R(\theta)(1+N)^t} \, dr_i = \frac{2a(\theta-r)}{(\theta-1)e^{-\theta}(1+N)^t} + \frac{2ae^{-\theta ln(1+N)}}{R(\theta)(1+N)^t} \quad (28)
\]

According to Equations (26)-(28) and through considering a = 1, the total expected desirability function for a customer (D) is obtained as of Equation (29):

\[
D = \sqrt[4]{d(BW), d(EW), d(N_{EW}), d(N_{BW})} \quad (29)
\]

4. THE INTEGRATED SUPPLY CHAIN OF AFTER-SALES SERVICES MODEL

After the introduction of the model components, including viewpoints of manufacturer, third party and customer, the integrated supply chain of after-sales services model can be presented as follows:

\[
\max D = \sqrt[4]{d(BW), d(EW), d(N_{EW}), d(N_{BW})} \quad (29)
\]

\[
\min TC_{3P} = ECM_{EW}(\Delta m) + EPM_{EW}(\Delta m) + ES_{EW}(\Delta m) \quad (30)
\]

\[
\min TC_{CM} = C_{CM} \int_0^{BW} h(t) \, dt \quad (31)
\]

Subject to:

\[
(15), (16), (18), (21), (25), (26), (28) \quad (32)
\]

\[
\Delta_{min} \leq \Delta \leq \Delta_{max} \quad \text{integer} \quad (33)
\]

\[
BW_{min} \leq BW \leq BW_{max} \quad \text{integer} \quad (34)
\]

\[
EW_{min} \leq EW \leq EW_{max} \quad \text{integer} \quad (35)
\]

The proposed model is an integer non-linear multi-objective problem. Achieving the optimal solutions for this type of models is practically impossible in large-size problems. So, in the next section, to optimize the proposed model, a multi-objective solution approach develops based on scatter search.

5. MULTI-OBJECTIVE SCATTER SEARCH ALGORITHM

In general, two approaches are used to optimize multi-objective problems. First, the model objectives are combined in a single objective, while in the second method a set of non-dominated solutions (Pareto-set) are extracted by algorithms such as NSGA-II and MOPSO [19]. In this paper, a multi-objective scatter search algorithm (MOSS) are developed for extracting Pareto-set. Scatter search is an exact strategy that was presented for the first time by F. Glover [20] and is applied well to solve combinatorial optimization problems [21]. MOSS steps are as follows:
6. NUMERICAL EXAMPLE

In this section, for evaluating the integrated supply chain of after-sales services model via MOSS algorithm, a set of numerical examples is presented. To investigate the validation of the proposed problem-solving algorithm, the exhaustive-search technique was employed. Both approaches were coded in MATLAB R2013a, and all calculations were implemented on a system with the following configuration: Core i5/CPU 2.4 GHz/RAM 4GB.

It is assumed that the probability distribution function of product failure process is a two-parameter Weibull distribution (according to Equation (36)) with the shape parameter $\beta$ and scale parameter $\alpha$.

$$
 f(t) = \frac{\beta}{\alpha} t^{\beta-1} e^{-\left(\frac{t}{\alpha}\right)^{\beta}}, \quad t \geq 0, \beta > 0
$$

Moreover, function $\delta(m)$ is defined as follows:

$$
\delta(m) = 1 - \xi m
$$

In Equation (37), the parameter $\xi$ is a number in the range [0,1] which regulates the PM level. Table 1 shows the data of numerical examples, including parameters of third-party’s maintenance strategy, product lifetime, risk and desirability functions related to customers and the MOSS approach.

It should be noted that the parameter setting of MOSS algorithm was performed based on primitive experiments.

For appropriate evaluation of the proposed model, the numerical example is investigated when it is put in $C^x \in \{400,500,\ldots,1000\}$, $C^{\text{SM}} \in \{200,300,\ldots,800\}$.
\( C^M_{CM} \in \{400,500,...,800\} \) and \( \theta \in \{1.5,2,...,4.5\} \). Hence, numerical example includes 119 scenarios. In addition, for accessing exact solutions through exhaustive search method, variables of the problem were considered in ranges \( BW \in \{0,0.5,...,3\}, EW \in \{0,0.5,...,7\}, \Delta \in \{1,2,...,52\} \) and \( m \in \{1,2,...,10\} \). Table 2 presents the obtained results from optimization of the integrated supply chain of after-sales services model via the MOSS algorithm and the exhaustive search algorithm for the 119 scenarios.

### TABLE 1. Information of the numerical examples

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<th>Value</th>
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### TABLE 2. Results of optimizing the proposed model based on MOSS approach and exhaustive search algorithm

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</table>
The NPS column shows the number of obtained Pareto-set solutions (NPS). The MS column shows the rate adaptation of the obtained NPS of the MOSS algorithm with the NPS of the exhaustive search algorithm. The MS indicator is calculated as follows:

\[
MS = \frac{SNPS}{NPS_{\text{Exhaustive search}}} \quad (38)
\]

In the above equation, SNPS indicates the number of Pareto-set solutions of the MOSS algorithm found also in Pareto-set of the exhaustive search algorithm \(NPS_{\text{Exhaustive search}}\). Additionally, the CPU column indicates the solving time per seconds.

### 7. Conclusion

The integrated supply chain of after-sales services model was developed for supporting manufacturer, third-party and customer in the present study. To optimize the model, a multi-objective scatter search approach was developed. The results indicated that with the increase in costs of corrective maintenance, the third-party has to reduce the time interval between preventive maintenance actions in order to prevent increasing of product failure rate. When the majority of customers are risk-averse, product failure has
remarkable effects on their desirability. In this condition, the manufacturer should prolong the basic warranty period for enhancing the customers’ desirability level, and the third-party for keeping this level and also reducing extended warranty costs should apply PM actions with higher levels. When the majority of customers are risk-taking, there is possibility for the manufacturer and the third-party to reduce their costs and keep customer desirability at an appropriate level by reducing the length of the warranty period. The results also indicated that the MOSS algorithm has high efficiency in extracting non-dominated solutions so that in the worst case, 89.1% of the obtained solutions were consistent with exact solutions of the exhaustive search method. In the present study, the maintenance logistics and spare parts management were not discussed, which can be investigated for the further research.

8. REFERENCES

The Integrated Supply Chain of After-sales Services Model: A Multi-objective Scatter Search Optimization Approach

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