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Developing Service Operations Strategy for Optimal Delivery of Long-Term Service Agreements

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Abstract

Long-term service agreements (LTSAs) for the maintenance of capital-intensive products are gaining popularity. Without a thorough understanding of risk exposures and their impact on service delivery, a provider is exposed to the possibility of extensive losses as well as endangers the products' end-consumers. In this article, we develop a rigorous risk assessment and management framework for developing an optimal service operations strategy for the delivery of LTSAs. The framework includes several important sources of risks, such as, engineering reliability, maintenance, service infrastructure, contract definitions, and the financial structure of the service. The goal of LTSA management is to satisfactorily meet the service guarantee while minimizing risk exposures and costs of service delivery. The framework allows simulation-based optimization to obtain an optimal service strategy and risk management, which can be used to develop a detailed tactical service delivery plan. The single LTSA based framework will also benefit the management of a portfolio of LTSAs.

Keywords

Long-term service agreement, service operations strategy, strategic management, continuous simulation

1. Introduction

In today's services oriented economy, providing better service to customers is an essential growth strategy. A particular service provided today is a service guarantee for high technology, high cost, long-lived products, e.g., locomotive engines, gas turbines, and aircraft engines. These agreements, often called long-term service agreements (LTSAs), are agreements between a provider and a customer that make the provider responsible for delivering guaranteed output of a product to the customer.

LTSAs are considered beneficial by both the customers and the providers. The customers often has limited technical knowledge of the product compared to the provider, and they can eliminate maintenance infrastructure and spare part inventory costs by purchasing an LTSAs and transfer the responsibility of maintaining the product over to the provider. The providers capitalize on their knowledgebase to generate new revenue streams and establish long-term relations with the customers. However, the benefits of LTSAs can be realized only if they are delivered efficiently.

Figure 1: Normative view of effective management of LTSAs

Efficient management of LTSAs appropriately allocates the responsibility of risks into the most suitable hands. Figure 1 presents a normative view for the management of LTSAs. The customer transfers risks of operating and maintaining the product to the provider via purchase of an LTSA. The provider plays the central role in delivering the service, where it develops an effective risk management and a satisfactory service operations strategy. Risks to which the provider is exposed can be divided into three categories, strategic, operational, and extreme-event risks [1]. Some risks beyond the provider's control, e.g., extreme-event risks, are transferred to a third party (e.g., insurance companies) via purchase of appropriate insurance. Risks of future technological changes and changes in government regulations are transferred back to the customer through a renegotiation clause in the contract.

In this paper we create a quantitative framework for risk assessment of delivery of LTSAs from the provider's perspective, since the provider plays the most critical role in defining and delivering the service. The framework focuses on the analysis of the strategic risks and includes several important sources of risks, e.g., engineering reliability, maintenance, service infrastructure, contract definitions, and the financial structure of the service.

The problem of developing a strategy for service delivery of LTSAs deals with designing end-to-end service operations for maintaining the functionality of the product. Therefore, it combines several features of maintenance management, inventory management, service operations management, and financial and risk management problems [2-5]. The provider needs to develop a maintenance strategy to ensure long-term functionality of the product by putting in place supporting service infrastructure. Maintenance activities include proactively replacing components in the product. Hence, the provider maintains and manages an inventory level of components with minimum inventory costs, while making sure the service is delivered satisfactorily. The provider has to design an efficient service operations process and the facilitating service infrastructure in order to meet the customer's requirements, and create adequate risk management plans conforming to the provider's business strategy. Our challenge is, therefore, to create an integrated risk management framework, which takes into account these features in order to find a service operations strategy for optimal delivery of LTSAs. The rest of this paper is organized as follows. We develop the framework in Section 2. This is followed by a discussion of simulation algorithm, which analyzes the risk of service strategy in Section 3, followed by the conclusion in Section 4.

2. Developing the framework

This section develops models pertinent to facilitating effective service delivery. Sources of risks that are important are incorporated in the framework as shown in Figure 2. To develop the framework, we employ a bottom-up approach, where the provider needs to completely understand risks at the lower levels before it can progress to analyze risks at the upper levels.

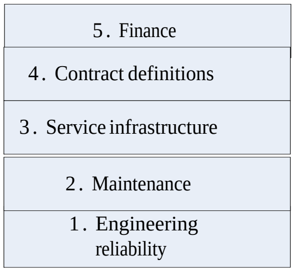

Figure 2: Overview of model development.

The framework begins with the construction of engineering reliability property of the product where we create a models to evaluate the condition or the health of the product (level 1 of Figure 2). Employing condition based maintenance (CBM), the provider makes proactive maintenance decisions based on the condition of the product. In level 2 of Figure 2 models pertinent to maintenance are developed. This is followed by the analysis of the service infrastructure. Service infrastructure models capture the behavior of a monitoring system and evolution of inventory level. Contract specification of level 4 of Figure 2 stipulates the penalty fee structure. Finally at the top, level 5 in Figure 2, we create a revenue model and assess the financial risks of the service for the provider.

2.1 Engineering reliability

The objective of this section is to develop a model for the evolution of the condition of the product over time. The condition or the health of the product (measured as deterioration) is constructed in terms of information pertinent to functionality of the product, e.g., temperature, pressure, and vibration, obtained from sensors-based monitoring systems. The product degrades continuously over time with randomness. The deterioration of the product consists of two parts, a continuous deterioration and a jump (sudden change) in deterioration. The deterioration of the product can described as follows.

$$\Delta X_t = \alpha(X_{t-1}, t)\Delta t + \beta(X_{t-1}, t)\Delta W_t, \tag{1}$$

$$\Delta C_t = f(X_t)\Delta t, \tag{2}$$

$$J_t = U_t I_{\{N(t^+)-N(t^-)=1\}}, \tag{3}$$

$$D_t = C_t + J_t, \tag{4}$$

where X_t is an Ito process, $\alpha(X_{t-1}, t)$ is the deterministic rate of increase in deterioration, and $\beta(X_{t-1}, t)$ is the stochastic rate of increase term, called the diffusion term. ΔW_t is a Weiner process. $f(\bullet)$ can be any positive integrable function, such as, exponential function. J_t is a jump deterioration process. $I_{\{N(t^+)-N(t^-)=1\}}$ is an indicator function for a jump, $N(t)$ is the number of jumps in time t. U_t is the intensity of a jump at time t. C_t and D_t are continuous deterioration and the total deterioration of a product at time t, respectively.

2.2 Maintenance

Maintenance activity aims to maintain the product in a good functional state and to minimize malfunctions and eliminate failures of the product, since malfunctions or failure result in disruption in production, reduction in quality, and severe loss of capital. The provider sets pre-specified trigger events for the product so that a suspicious or a prone to failure state is detected before the product succumbs to failures, since the cost of failure is extremely high compared to the cost of maintenance. The provider needs to map the trigger events with threshold level for deterioration. After identifying the threshold levels, the provider needs to assign an appropriate maintenance action to each trigger event so that a balance between cost of maintenance and cost of failure is achieved. In this paper, a maintenance action is comprises of a primary and a secondary maintenance action, where the primary action targets the component in suspicious condition, while the secondary action is an opportunistic maintenance to further improve the condition of the product while it is in maintenance.

To assess the risks of service delivery, the provider needs to determine the effect, the costs, and the downtime of maintenance actions. The effect of maintenance actions is determined using a correction factor model, where the correction factor of a maintenance action (CF_A) is a product of correction factor due to the primary maintenance action (CF_{A_P}) and that of the secondary action (CF_{A_S}), i.e., $CF_A = CF_{A_P} \times CF_{A_S}$. Similarly, cost and downtime of a maintenance action are found using a multiplicative model. A multiplicative model is used because the secondary action is an opportunistic maintenance, hence it enhances the impact of the primary action. Maintenance may not be perfect due to several factors, such as, poor condition of repair equipment, inexperienced repair personnel, etc. Risks of maintenance are modeled by four outcomes, perfect/imperfect primary/secondary actions.

2.3. Service infrastructure

Service infrastructure facilitates and supports the delivery of the service. In this paper we focus on two important components of service infrastructure, inventory management and impact of monitoring systems.

2.3.1 Inventory

The level of inventory significantly affects the downtime of the product, since maintenance actions can be performed if and only if there are parts available in the inventory. Thus, the provider needs to control the inventory level such that there are no inventory shortages, but do this at minimum cost. Evolution of the inventory level is as follows.

$$I_{t+1}^i = I_t^i - N^i(A_{t+1}) + R_{t+1}^i + P_{t+1}^i, \tag{5}$$

where I_t^i is the inventory level of type i component at time t. $N^i(A_t)$ is the number of type i components needed for maintenance action (A) at time t. R_t^i and P_t^i are the number of type i components repaired or purchased at time t, respectively. In our analysis we categorize components into two types, critical or non-critical.

The delay of downtime due to inventory shortage is found by comparing the number of components we need for a maintenance action with a fraction of the current inventory level. If the fraction of the inventory level is less than the number of components needed, it is highly likely that there is inventory shortage. The waiting time is generated from an underlying distribution to represent the delay due to an inventory shortage.

2.3.2 Monitoring system

A monitoring system plays a critical role in supporting the delivery of LTSAs, since products on which LTSAs are extended are usually capital intensive, thus justifying the sophisticated monitoring system and condition-based maintenance. A monitoring system helps the provider better assess the condition of the product and, therefore, make better proactive maintenance decisions.

Errors in assessment using the monitoring system are of Type I or Type II kind; Type I error corresponds to when the monitoring system interprets the condition of the product as good, but it in fact is not. Hence, the true condition of the product is worse than is perceived. Type II error is when the monitoring system interprets the condition of the product as bad, but it in fact is good. Therefore, the actual deterioration of the product is lower than the perceived level. Errors in the monitoring system are captured by the fluctuation of the threshold levels defining trigger events as shown in Equation (6), this model choice is reasonable since the monitoring system is shared by many LTSAs, thus the risks of the monitoring system affects all LTSAs to same degree.

$$T_{e,t} = \hat{T}_e + \varepsilon_{e,t}, \tag{6}$$

where $T_{e,t}$ is the observed threshold level of a trigger event e at time t. $\hat{T}_e$ is the true level of the trigger, and $\varepsilon_{e,t}$ is the level of error (misinterpretation) of a trigger e at time t. The error process is modeled as a Markov chain.

2.4 Contract definitions

LTSAs are well-crafted contracts between a provider and a customer. A contract generally covers financial obligations, engineering and functional deliverabes, and legal bindings. The financial obligation and penalty fee structures relate to the price and the payment plan for a contract. The engineering aspects concern the functionality of the product, where the provider guarantees the functionality of the product in terms of performance measures and maintenance/operations protocols or constraints. The performance measure can be, for example, the availability and the throughput of the product. The legal binding can define contract duration, effective date, and liabilities of both parties.

Penalty fees are levied if a contract is breached. For instance, the provider cannot fulfill the service delivery to his customer. We model the penalty fee as follows.

$$PF_m^i = C_i^{PF} \times \max\{0, PM_g^i - \overline{PM_m^i}\}, \tag{7}$$

where PF_m^i is the penalty fee of performance measure i in month m. C_i^{PF} is the penalty rate of performance measure i, which may be set very high compared to the costs of maintenance actions and inventory, in order to enforce the priority of delivering the guaranteed service. PM_g^i and $\overline{PM_m^i}$ are the guaranteed performance level of type i and the level actually delivered in month m, respectively.

2.5 Finance

A financial model integrates the costs incurred in levels 2-4 in Figure 2 and the revenues received. From a financial perspective, the provider conducts three main activities, collects the contract premium, incurs the costs of service delivery, and invests the available funds to maximize profit.

In our paper, we assume that the revenue structure is linear, where the customer pays the premium (Y_m) on a monthly basis, i.e., $Y_m = a \times m + b$. In each period, the provider can evaluate his surplus or shortfall of the cash flow, which is the difference between the revenue received and the total cost of the service. The total costs comprise of maintenance costs, failure costs, inventory costs, and penalty fees. The provider accumulates or depletes his reserve funds (RES) in each month. The reserve fund in month m (RES_m) can be found as follows.

$$RES_m = RES_{m-1} + NCF_m, \tag{8}$$

where NCF_m is the net cash flow in month m.

2.6 Risk measures

We discuss rigorous risk measures used to evaluate long-term risk exposures for the provider in this section. Appropriately chosen risk measure is important for strategic management. These should conform to the provider's business strategy. In our paper, we select four risk measures for evaluating risks for the provider. The risk measures are as follows.

- Mean-variance measure: $RM_1 = E(RES_M) - Std(RES_M)$.
- Cumulative sum of mean-variance measure: $RM_2 = \sum_{m=1}^{M} [E(RES_m) - Std(RES_m)]$.
- Cumulative sum of 100α % VaR -variance measure: $RM_3 = \sum_{m=1}^{M} [VaR_{100\alpha}(RES_m) - Std(RES_m)]$.
- Cumulative sum of mean – probability of negative reserve measure: $RM_4 = \sum_{m=1}^{M} [E(RES_m) - P(RES_m < 0)]$.

The objective function of the provider is to minimize risks, which is the weighted average of these four risk measures.

3. Simulation algorithm

This section implements the framework and develops an algorithm to analyze risks of service delivery. The problem of assessing risks of an LTSA is complex and is not solvable analytically, since the problem involves several controlled stochastic processes. As a result, we obtain the solution numerically using continuous simulation techniques. Figure 3 presents a flow chart for the simulation algorithm. After a complete specification of the problem in step 1, we begin the simulation process in box 2 of Figure 3 where we find the deterioration of the product (D_t). After finding the deterioration of the product, the provider checks if the deterioration falls in a trigger zone (boxes 3 and 4 in Figure 3). If the deterioration does not fall in a trigger zone, we increment the time by one period and go to box 2 of Figure 3. If the deterioration falls into a trigger zone, a maintenance action is needed (box 5 in Figure 3). The provider assesses the performance measure every month. After evaluating the performance measures, the provider calculates the penalty fee, the total cost, and the reserve fund for each month (box 6 in Figure 3). The simulation iterations continue until reaching the planning horizon (T). At the end of the planning horizon, the provider evaluates the risks of service delivery by calculating the risk measures and the objective function (box 10 in Figure 3).

3.1 Analysis of optimal maintenance action obtained at the engineering level

We present results to illustrate implementation of the simulation, where we analyze the risk of service delivery, with the maintenance strategy obtained by considering maintenance costs alone. The provider finds the optimal maintenance action minimizing the maintenance costs over the long run based on a detailed engineering properties model [2]. After finding the optimal maintenance action, the provider develops a consistent service strategy based on these maintenance actions.

We implement the simulation in MATLAB on a Pentium 4 machine with 3.2 GHz processor and 1 GB memory. We simulate 3000 replications, with a run time of 1000 seconds, to evaluate the risks of the service strategy. The total costs of the service strategy are $37,667. The total costs consist of maintenance costs ($16,961), inventory costs ($14,101), and penalty fees ($6,604). The standard deviation of the total costs is $7,652.64. Since the costs of failures are extremely high, the maintenance action set for each trigger event is aggressive. As a result, we don't see occurrence of failures in our simulation. These estimates are for a representative choice of cost structure. The inventory policy implemented is an (s,S) reorder policy, where the reorder levels (S) are 5 for critical and 10 for non-critical components, and the reorder points (s) are 1 for critical and 3 for non-critical, respectively. We assume that the number of critical components is less than the number of non-critical components in the product.

We continue the analysis by searching for the optimal inventory policy, choosing between (s,S) and (Q,r) reorder policies for comparison. We find that the (Q,r) policy with Q^* at 2 for critical and 6 for non-critical components outperforms the (s,S) policy. The optimal inventory policy reduces the total cost by 3.6%. Finally, we optimize the revenue parameters, assuming a linear revenue model. The optimal revenue parameters are found to be: a^* (slope) =-1.5, and b^* (the intercept) is 746. The optimal revenue parameters are as expected, since the linearly decreasing revenue model allows the provider to build the reserve early in the contract period. Therefore, the provider reduces the risk of insolvency.

4. Conclusions

In this paper, we develop a quantitative framework to analyze risks of service delivery of LTSAs and solve using continuous simulation techniques. Appropriate risk measures are created to assess the risks of a service strategy. The parameters for the engineering reliability are estimated from [1]. Moreover, the parameters and the models used in our paper are partially qualitatively validated by experts in the area of LTSAs. However, a detailed quantitative calibration and validation of the models is part of continued work.

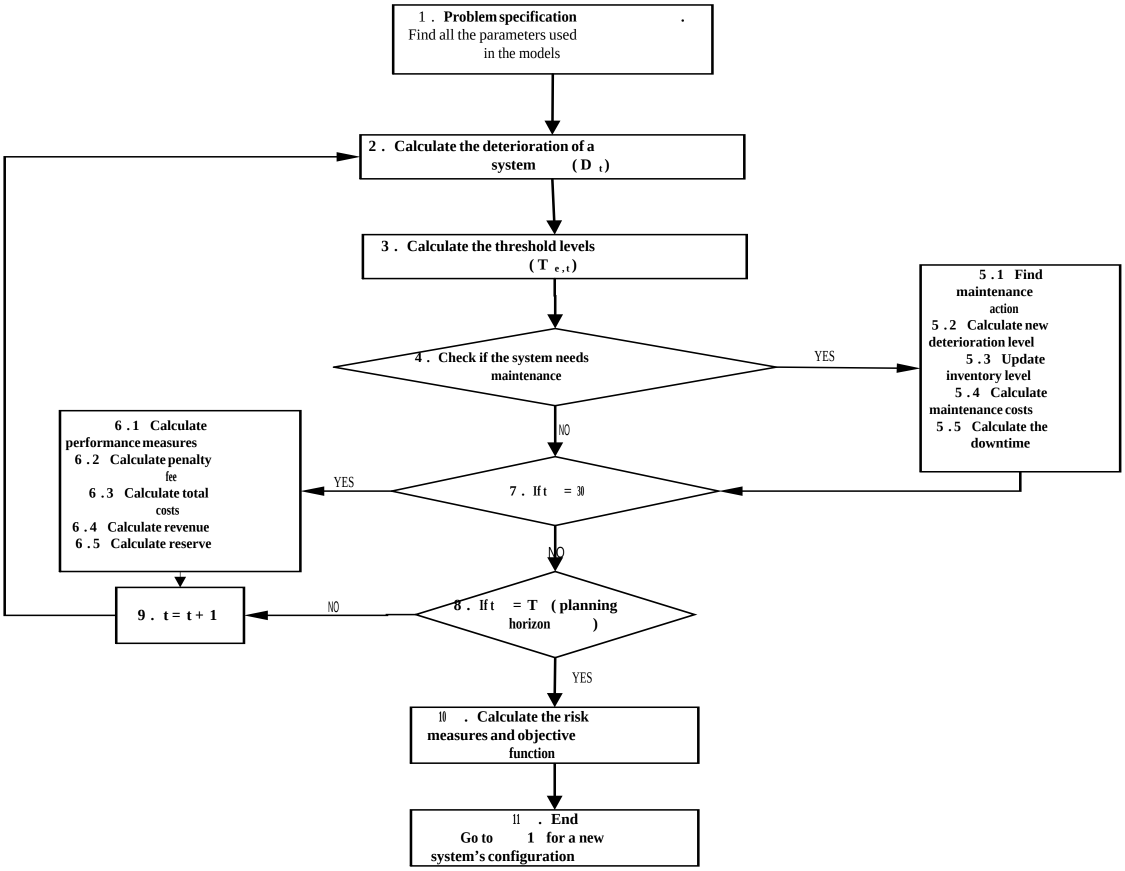

Figure 3: A flow chart of the simulation algorithm

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