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A game-theoretical approach for optimizing maintenance, spares and service capacity in performance contracting

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ABSTRACT

Recently the service industry is transitioning from material-based contracting to performance-based contracting. This paradigm shift enables the supplier to maximize the profit by attaining the system performance goal, while the customer is able to lower the asset ownership cost with assured system availability. Prior studies usually focus on a single stakeholder, either the supplier or the customer, in searching for the optimal decisions. Under game-theoretical framework, this paper proposes a multi-party, multi-criteria, and multi-item service delivery mechanism to maximize the utilities of all the stakeholders. The goals are achieved by jointly optimizing the maintenance, the spares inventory, and the repair capacity under the game-theoretical framwork. We prove that the supplier's actions on parts replacement time, spares stock level and repair cycle times are fully observable to the customer. Hence a first-best solution is guaranteed without moral hazard issue. Numerical studies from wind industry show that a single or a consolidated multi-item contract could be advantageous over multiple single-item contracts as it ensures a higher profit margin at a lower customer's cost.

1. Introduction

Performance-based contracting (PBC) is often referred to as "performance-based logistics" in defense sector; and it is called "payment by results" in healthcare industry (Jiang et al., 2012). In equipment industry, PBC is envisioned to lower the asset ownership cost while assuring the system reliability performance. Operational availability, parts fill rate, and logistics response time are often designated as the key performance measures to assess the service outcome. PBC differs from material-based contracts (MBC) in that the supplier under PBC is compensated for the system outcome, not for the actual labor and materials transacted. Successful PBC programs have been reported in the U.S. military showing that aircraft operational availability has increased by 15–20% (Berkowitz et al., 2004).

Extant literature in PBC (see Kim et al., 2007; Nowicki et al., 2008; Mirzahosseinian and Piplani, 2011; Jin and Wang, 2012; Selcuk and Agrali, 2013) generally agree that an effective PBC program should concentrate on the following performance drivers, namely reliability, spares inventory, repair capacity, system usage, and fleet size. However, an in-depth analysis of service profit and performance risks considering maintenance policy has been overlooked. Managing spare parts supply differs from manufacturing or production inventories in that the stock levels are largely a function of how the equipment is used and how it is maintained. Preventive maintenance is often treated as an effective means to warrant the system availability by pro-actively replacing aging components prior to failure. However, maintenance may overload the service supply chain due to escalated parts returns and repair tasks. Therefore, it is imperative for the supplier to balance the maintenance frequency with the repair and the spares inventory to achieve the contractual goal.

While a variety of inventory and logistics models have been developed in literature, the majority of these studies are confined to a single stakeholder, either the customer or the supplier. This paper aims to fill this void by proposing a multi-party, multi-criteria, and multi-item contracting model in which the supplier adopts the preventative maintenance as a lever to manage the availability of capital equipment at customer site. We focus on original equipment manufacturers (OEM) who design and produce capital goods and also provide after-sales support. Such products include wind turbines, computer servers, and aircraft engines, among others. The motivation of the research is to design and implement a win-win PBC program by attaining three objectives: (1) maximizing the service profit; (2) reducing the levelized system cost; and (3) attaining the reliability and availability goal.

The contribution of the work lies in three aspects. First, we present a unified operational availability model that accommodates

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eight key performance drivers, including reliability, usage, maintenance, spare parts, fleet size, parts replacement time, and parts reconditioning and repair cycle times. Second, we propose a game-theoretical contracting framework to accommodate five overarching performance measures, namely operational availability, mission reliability, logistics response time, logistic footprint, and cost per unit usage. Third, we show that the supplier's decision on parts replacement times, spares stock level and parts repair cycle time is fully observable to the customer, hence avoiding the moral hazard issue. In game theory, moral hazard occurs when one player takes more risks because someone else has to bear the burden or consequence of those risks.

This remainder of the article is organized as follows: Section 2 reviews the related literature. Section 3 presents a unified operational availability model for single-item and multi-item systems. In Section 4, we analyze the system lifecycle costs perceived by the OEM and the customer, respectively. In Section 5 principal-agent contracting models are formulated for single-item and multi-item systems, respectively. In Section 6, the proposed method is demonstrated on wind industry and managerial insights are derived, and Section 7 concludes the paper.

Notations

A, A_s=	availability of component and system, respectively
n=	number of systems in a fleet
m=	number of component types in a system, i=1, 2,…, m
λ_f=	failure replacement rate under a PM policy
λ_p=	planned replacement rate under a PM policy
λ=	aggregate component replacement rate, and $\lambda=\lambda_p+\lambda_f$
s=	base-stock level of spare parts, decision variable
τ=	maintenance time, decision variable
t_p=	cycle time for reconditioning a part, decision variable
t_r=	cycle time for repairing a part, decision variable
t_s=	time for performing a repair-by-replacement job
$\overline{T}_d$=	system mean downtime
$\overline{T}_o$, $\overline{T}_s$=	system mean operating and standby times, respectively
$\overline{T}_u$=	system up time, and $\overline{T}_u=\overline{T}_o+\overline{T}_s$
$R(t)$=	reliability function
$F(t)$, $f(t)$=	cumulative distribution and probability density functions, respectively
O=	steady-state inventory on-order
$\overline{T}$=	mean-time-between-failures in calendar time
α, β=	inherent Weibull scale and shape parameters, respectively
ρ=	usage rate, and $0<\rho\le 1$
r=	interest rate compounded annually
h=	equipment loan payment period in years
ϕ_1=	equipment capital recovery factor
C_a=	annualized system cost
C_e=	system purchase cost
C_o=	annual system operating cost
C_d=	annual system production losses
C_s=	levelized system cost
C_m=	annual maintenance and logistics support cost
$c^{(f)}$, $c^{(p)}$=	production loss in a failure or a planned replacement
ϕ_2=	spare part capital recovery factor
k=	number of contract years
c_1=	spare part unit cost
c_2=	holding cost per unit per year
$c_3(t_p)$, $c_4(t_r)$=	costs for reconditioning and repairing a part, respectively
$c_3^{(b)}$, $c_4^{(b)}$=	baseline reconditioning and repair cost of a part, respectively
$t_p^{\min}$, $t_r^{\min}$=	shortest reconditioning and repair cycle times, respectively
$t_p^{\max}$, $t_r^{\max}$=	longest recondition and repair cycle times, respectively
γ_1, γ_2=	parameters in the reconditioning/repair cost models
θ=	maintenance frequency criterion specified by the customer
a, b_1, b_2=	base payment, reward rate and penalty rate, respectively
π_1, π_2	service profit and levelized cost for single-item systems, respectively
Π_1, Π_2	service profit and levelized cost for multi-item systems, respectively

2. Literature review

We revisit the scholarly works related to the spare parts logistics (SPL) planning and the joint maintenance-SPL models. For reviews on maintenance optimization, readers are referred to Nicolai and Dekker (2006). Throughout the paper, component, part and subsystem are used interchangeably, representing a line replaceable and repairable item in the system or equipment.

2.1. Spare parts logistics models

Since Sherbrooke (1968) introduced the multi-echelon technique for recoverable item control (METRIC) model, many interesting works have been developed to generalize or extend this pioneering repairable inventory model. Such generalizations include multi-item, multi-indenture, transshipment, capacitated repair, variable fleet size, performance commitment, and adaptive stock policy (see Graves, 1985; Lee and Moinzadeh, 1987; Axsäter, 1990; Sleptchenko et al., 2002; Zijim and Avsar., 2003; Caggiano et al., 2006; Kim et al., 2007; Jeet et al., 2009; Dekker et al., 2013; Selcuk, 2013). The goal of the METRIC and its variants is to allocate the repair capacity and the inventory level to ensure the parts fill rate, or to lower the holding or backorder cost subject to service level requirement. We refer to Kennedy et al. (2002) for a thorough and extensive review on repairable inventory models. Kim et al. (2007) design a performance-based service contract using game theory. Our model resemble to theirs in the sense that both aims to maximize the supplier's profit while lowering the customer's cost. A major difference is that our principal-agent contracting model guarantees full service efficiency as the supplier's action is fully observable to the customer without moral hazard. Lin et al. (2013) generalize the risk-averse contracting model of Kim et al. (2007) to design a PBC program between a foreign government and a 3rd part logistics supplier for defense systems. Recently attempts have been made to endogenize the reliability as a decision variable along with the parts stockage to seek a better service supply chain design (Öner et al., 2010; Jin and Tian, 2012; Selcuk and Agrali, 2013). These studies show that excessive inventory and logistics footprint could be avoided had higher reliability been built into the product.

For repairable inventory, the stock level is also dependent upon the repair capacity and the forward-and-backward transportation times. Though various models have been developed to jointly allocate the maintenance and the spare parts inventory, the repair capacity has long been excluded as decision variables. Repair cycle