Signaling Product Quality with After-Sales Service Contracts

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Due to its complex nature, after-sales service support for systems such as aircraft engines is commonly outsourced to the vendor. A key input to contracting for such support is system reliability. When product-technology is new, the vendor often knows more about reliability than the buyer, potentially leading to contractual inefficiencies. This paper examines the role of after-sales contracts as a mechanism for signaling reliability. We focus on two commonly encountered categories of contracts, the (generalized) Time and Material contract and the performance-based contract (PBC). We find that they differ substantially in their ability to signal reliability, achieve system efficiency, and allocate rents in the supply chain. While the vendor of a reliable product is always better-off with PBC, the same is not true for the buyer or the vendor of an unreliable product. This sheds new light on the on-going debate regarding the relative merits of the two contracting strategies.

Key words: signaling games; performance-based contracting; aerospace sector; aftermarket; service operations

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1. Introduction

Product maintenance, repair, and overhaul (MRO) is an important business area in the aerospace industry, generating \$111 billion in revenue in 2009, with \$43 billion attributed to the commercial airline sector (Standard and Poor's 2011). In many cases, the MRO service business in fact brings more profits to the aircraft system and subsystem providers such as Boeing, EADS, GE, Rolls-Royce, and Pratt & Whitney than do the sales of their products (Dennis and Kambil 2003).

For the customer organizations in this industry, namely government (defense sector) and airline companies, product reliability is a major concern: the products they acquire from the vendors—aircraft engines, for example — might occasionally fail. While failures — which we define as any instance of unscheduled maintenance — are relatively infrequent (e.g., for aircraft engines, the mean time between failures (MTBF) is of the order of 2 to 5 years (Guajardo et al. 2011)), they have significant operational and financial consequences. For example, unscheduled maintenance on a wide-bodied aircraft could cost as much as ten times the capital outlay over the operating life of the aircraft (Hopper 1998).

Since the products are complex and built on proprietary technology, customers have to rely primarily on the services and spare parts provided by the same vendor who sold the product. In outsourcing MRO services the customers face nontrivial challenges. The absence of competition leads to a weaker bargaining position for the buyer during service contract negotiation with the vendor of the chosen product model (GAO 2006). Moreover, the challenge is magnified if the buyer decides to acquire a newly developed product since the vendor possesses superior knowledge about product reliability. This information regarding product reliability is not disclosed to the buyer (Adamides et al. 2004) and it is difficult to assess independently. For example, the OEM's databases describing material properties of alloys used are not publicly available (Kappas 2002).[1]

Thus, it is challenging for the buyer to determine how much value he will get by accepting the terms of a maintenance service contract that depends heavily on the frequency of product failures. Consider, for example, a time and material (T&M) contract which is prevalent in the industry. Since the buyer pays for labor, spare parts, and other incidentals each time the product fails under the T&M contract, the vendor would have to make concessions in the maintenance contract proposal if both parties know that the product is highly prone to malfunctions. However, a buyer who lacks this information is limited in his ability to demand such concessions since he can only guess whether the product he acquires will be reliable or not. On the other hand, the vendor may not be able to effectively convey to the buyer the reliability of her product even if she wanted to; as product failures are rare events, a buyer cannot independently validate the vendor's claim of reliability unless the product is used for many years.

As a result, there is potentially a high degree of inefficiency in MRO outsourcing of new products due to the presence of information asymmetry between a vendor and a buyer. With the buyer not being able to objectively verify the vendor's claim of product reliability at the time of contracting, the vendor and the buyer engage in a game in which the buyer tries to infer the true quality of the product from the maintenance contract terms, which the vendor may use to either signal high reliability or conceal low reliability. Thus, contract type plays a significant role since the contract's innate structure constrains how well it can be used as a signaling mechanism. This aspect of the MRO service contracts has never been investigated in the literature before. In this paper we aim to bridge this gap by proposing and analyzing a stylized model of product reliability signaling through

[1] The difficulty in assessing reliability is reflected in the aircraft purchasing decisions of the defense sector as well. Boito et al. (2009) studies the maintenance outsourcing practises at the U.S. Air Force and finds that managers at 6 of 12 defense programs stated lack of access to technical data as a significant concern when negotiating contracts with vendors.

maintenance contracts, based on the observations of practice gathered from our interactions with managers in the aerospace industry.

In the aerospace industry there exist two main categories of maintenance contracts: resource-based contracts (RBC) and performance-based contracts (PBC). They differ by the basis of compensation for maintenance activities performed by the vendor. RBC is the more traditional of the two approaches and rests on the simple idea that compensation is proportional to the amount of resources utilized to repair a defective product. We define RBC as a generalized version of the popular T&M contract, allowing the vendor to share a fraction of the total cost of repair and spare parts incurred after failure incidents. Such cost sharing arrangements are ubiquitous in the defense sector of the aerospace industry and they are also found in the commercial sector, where limited or full warranty coverages are often bundled with product sales (Adler et al. 2009).[2] PBC is a fundamentally different concept, since the vendor under PBC is compensated based on the realized performance outcome (in particular, aircraft up-time) instead of the amount of resources utilized for repairs. For example, a typical PBC used in the aerospace industry specifies the rate at which a vendor will be paid per unit of time an aircraft or aircraft subsystem is functional, or equivalently, the rate at which the vendor will be penalized for each unit of product downtime.

PBC has gained traction in recent years—not only in the aerospace industry but also locomotive, energy exploration and mining, information technology and even healthcare—because many customer organizations view it as a simpler approach to manage outsourced maintenance operations without having to worry about the details of securing and accounting for the resources needed for repairs, a necessary step under RBC (GAO 2004, Pavans 2009). In fact, PBC is promoted as the centerpiece of the new business paradigm called "through-life management", which promises long-term service care for the products from initial sale to disposal (Ward and Graves 2007).[3] Despite widespread adoption of PBC, we observe that it co-exists with RBC. For instance, GAO (2004) reports that while all six of the interviewed companies in the commercial aerospace industry used PBC to some extent, the percentage of PBC usage varied from a low of 20% to a high of 90%. This study also found that companies opted for RBC arrangements particulary for new products. Ward and Graves (2007) report that the senior executives in the U.K. aerospace industry

[2] By incorporating cost sharing in RBC, we are able to generalize the implications of having a compensation rule based on resource utilization without being bounded by the narrow definition of a T&M contract, which is sometimes interpreted as the buyer being responsible for the entire repair-related costs.

[3] All the major vendors of aircraft engines offer some variant of through-life management solutions involving performance-based compensation. For instance, Rolls-Royce has about half its fleet of 12,000 engines on PBC through its TotalCare and CorporateCare programs. Some 40% of the combined GE and CFM International fleet of around 23,000 commercial engines are on PBC through the OnPoint Solutions program. Similarly, a third of the engine overhauls in 2009 at Pratt & Whitney were done under Fleet Management Programs - a form of PBC (Adler et al. 2009).

foresee continued support for the two business models: on the one hand, moving increasingly to a through-life management approach and, on the other, maintaining traditional business models for those customers that prefer it and for mature and legacy equipment. Even though we frame our discussion with the commercial aerospace industry in mind, our results are more generally applicable to outsourced MRO services.

The question remains as to whether the co-existence of the two contract types is a reflection of some customers preferring RBC, not just for maintenance of legacy products but also for new products. We investigate this issue in this paper: Given that the proposed terms of an after-sales maintenance contract of a new product may signal product quality that is unknown to a buyer, what are the situations in which PBC leads to a better equilibrium outcome than RBC does, and vice versa? What are the implications for different supply chain members?

We build a stylized model that captures the most important factors that influence the managerial decisions on after-sales maintenance contracting for new products. The vendor could possess a system with either high or low reliability, which is unknown to the buyer, and she makes a take-it-or-leave-it contractual offer to the buyer. We focus on how effective the two contracting approaches, i.e., RBC and PBC, are as a mechanism to signal product reliability, and whether an efficient outcome can be achieved. A critical operational feature of the setting is the inventory level of spare products, which substitute defective units and therefore offset product failures. When inventory is verifiable and therefore contractible, it may be used as an additional signaling device, and hence it plays a significant role. When it is unverifiable, the contract specification, in addition to signaling product reliability ought to also create incentives for maintaining the spare inventory level. We examine both cases in detail. Our analysis reveals a number of interesting managerial insights:

• We find that PBC allows the vendor of a reliable product to credibly signal her quality to the buyer, in a more cost effective manner than is possible with RBC. Using realistic parameters from the aerospace industry, we numerically estimate that these cost savings could be in the order of millions of dollars per month.

• We find that the form of PBC proposed in the literature and commonly used in practice, that requires contracting on product availability, does not always achieve system efficiency and therefore leaves money on the table. A more flexible and operationally practical variant that contracts on both availability and reliability can restore system efficiency.

• Despite the widespread notion held by many practitioners and documented in the extant academic literature, that PBC is superior to RBC in achieving system efficiency, we demonstrate that this is not necessarily the case; system efficiency may be attained under RBC as well. However, when this happens in equilibrium, the vendor of reliable products surrenders some rent to the buyer. This difference in equilibrium payoffs offers a possible explanation for the co-existence of

RBC and PBC in practice; some buyers would prefer RBC, while high-reliability vendors would favor PBC.

In summary, this paper is the first to analytically examine the role of after-sales contracts as a mechanism for signaling reliability. We find that RBC and PBC differ in their ability to signal product quality; achieve system efficiency; and allocate rents across the supply chain. While a vendor who possesses a reliable product is always better off with PBC than with RBC, the same is not true for the buyer and for a vendor with an unreliable product. By adopting a signaling perspective we offer new insights into the contracting strategies that are a subject of ongoing debates among practitioners.

2. Literature Review

Our work relates to three distinct streams of literature. The first explicitly deals with performance-contracts in service settings. The second stream, with which our work shares a methodological connection, is the literature on asymmetric information in operations management (OM). Finally, we connect our work to the literature that deals with the use of warranties as a signaling mechanism.

PBC in the context of after-sales services for aircraft engines has been studied in a Principal-Agent framework in Kim et al. (2007) and Kim et al. (2010). Papers that study PBC in service settings other than for aircraft engines include Roels et al. (2010), Gumus et al. (2011), and Jain et al. (2011). More generally, there is a rich stream of literature that deals with outsourcing of service processes. Papers under this theme include Benjaafar et al. (2007), Aksin et al. (2008), and Hasija et al. (2008). Our paper is closest in spirit to Kim et al. (2007) which investigates a setting in which the buyer proposes the terms of the PBC, while the vendor exerts private effort to reduce maintenance cost and invests in spare parts inventory. The paper shows that, in a setting with risk-neutral players, first-best (efficient outcome) can be achieved. However, with risk-averse players, the first-best cannot be attained and the optimal second-best contract involves a performance-related component.

While this stream of research has shown how PBCs align incentives between the vendor and the buyer in a setting with moral hazard, it assumes that the failure characteristics of the products are common knowledge. Our paper complements this line of research by studying a setting with asymmetric information: the vendor knows more about the system's reliability than the customer. We show that PBC can be an effective signaling device that allows the vendor to credibly communicate to the buyer the quality of the systems it sells and at the same time allows a reliable vendor to extract more rents from the buyer. Thus, our research points to a further benefit of PBC, namely its ability to signal quality. Another distinction from the aforementioned work, which primarily focused on the defense sector, is that our model applies better to the commercial aerospace industry where it is typically the vendor who initiates contracting.

Our paper is related methodologically to the OM literature on games of asymmetric information. Most of the research therein has focused on problems of adverse selection, in which an uninformed party moves first and offers screening contracts designed to elicit information from an informed party and improve the efficiency of the transaction (see Corbett et al. 2004, and Li and Debo 2009). While some papers do adopt a signaling framework instead (e.g., Anand and Goyal 2009, Cachon and Lariviere 2001), this paper is the first work that focuses on signaling in the after-sales service context.

The risk sharing and signaling capabilities of RBC and PBC result in characteristics similar to product warranties. Signaling product quality through mechanisms such as guarantees and warranties has a long tradition in economics (Gal-Or 1989, Lutz 1989, Riley 2001), marketing (Boulding and Kirmani 1993, Moorthy and Srinivasan 1995), and OM (Courville and Hausman 1979, Gumus et al. 2011). See Kirmani and Rao (2000) for an extensive survey of the literature. As per the classification-scheme proposed in this review article, the contracts that we analyze would fall into the category of cost-risking default-contingent signals. Such signals do not involve up-front expenditure yet credibly convey quality information. The underlying premise is that firms selling low-quality products will face higher costs for the same level of warranty than will high-quality firms, because low-quality firms' products are likely to require more frequent repair. In contrast to the common assumption in the quality signaling literature that product performance is specified exogenously, a critical distinguishing feature of our model is that the consequences of product failures can be mitigated through a managerial decision on spare inventory. This aspect creates new dynamics and enriches managerial insights. Another important difference between our work and extant literature is that in our paper the signaling is done within the context of a bilateral relationship, as opposed to a one-to-many interaction that is characteristic of a Business-to-Customer (B2C) setting with heterogeneous consumers. Insights from the B2C setting invariably do not carry over to the B2B setting because the latter precludes strategies that trade-off differences in consumer characteristics, e.g., price sensitivity, attitude towards risk, intensity of product-usage, etc. Finally, our primary interest is to contrast the performance of two specific and widely-used warranty-like contracts in an after-sales context, i.e., RBC and PBC.

3. Model

We study a supply chain that consists of two risk-neutral parties, a vendor and a buyer. To simplify analysis and streamline the exposition, we assume that the demand for product usage that the buyer sees is constant. To satisfy this demand, the buyer is considering the purchase of N identical copies of the newly developed product (which constitute a fleet of systems) from the vendor. The two parties negotiate the price of the N products and terms of the after-sales maintenance service contract. The fixed fee in the transfer payment (see §3.4) can be interpreted to be inclusive of product price. Consistent with the Principal-Agent framework, we assume that the vendor offers a take-it-or-leave-it contract to the buyer. The buyer accepts the contract if his payoff exceeds his outside option θ. At the time of contract offer the vendor is better informed about reliability of the product, through knowledge of inner workings of the product, internal test results, and sampling of product failure reports from initial deployment with other buyers. After the contract terms are exchanged, the buyer deploys the products to generate output. The duration of the contracting period is normalized to one.

3.1. Repair Facility and Inventory Policy

All assumptions in this subsection are adopted from Kim et al. (2007, 2011) that are based on the standard spare parts inventory management models. During the course of deployment the products fail occasionally due to malfunction, disrupting the buyer's system operation and triggering the vendor's repair operation. The products are repairable items, implying that they are not discarded upon failure but rather repaired and restored back to the working condition. A one-for-one base stock policy is followed for spares inventory control (Feeney and Sherbrooke 1966). A failed unit immediately enters a repair facility, which is modeled as an $GI/GI/\infty$ queue with an expected repair lead time, l, which in the context of aircraft engines is of the order of a few weeks. We assume that the distribution for repair lead time is exogenously specified (more on this assumption in §6.3). We denote the stationary distribution function for the number of system failures in the contracting period by $G(x)$ and the expected number of failures by μ. The fixed failure rate assumption is an approximation, because the repair process forms a closed loop cycle (i.e., repaired systems are reintroduced into circulation) with finite population. This implies that μ is a function of the number of working systems. However, this approximation is not very restrictive if the number of systems, N, is "large enough". In particular, if the failures follow a Poisson process then this approximation is known to be reasonable if $\mu l \ll N$. This assumption is commonly found in the spare parts inventory management literature and is consistent with practice (e.g., Sherbrooke 1968). In our model we approximate all discrete variables (such as backorders and spare inventory level) as continuous variables, in order to facilitate game-theoretic analysis. For a more detailed justification and numerical examples, see Kim et al. (2007, 2011).

A product failure may affect system availability, which is defined as the fraction of product up-time over the length of contract duration. System availability is unaffected if a spare product can be pulled from inventory to replace the defective unit immediately. If the inventory is empty at the time of failure, however, system availability is reduced until a repaired unit becomes available from the repair facility. This causes inventory backorder, denoted by B. Let F be the cdf of the inventory on-order, i.e., the number of repairs being performed at the repair facility at a given point in time. We assume that $G(x), F(x) = 0$ for $x < 0$ and their corresponding pdf functions $g(x), f(x) > 0$ for $x > 0$. For a given level of spares inventory s, then, the expected backorders in steady state is equal to $E[B|s] = \int_s^\infty (1 - F(x))dx$. Moreover, a one-to-one correspondence can be made between system availability and the expected backorders: availability is equal to $1 - E[B|s]/N$. Therefore, system performance can be measured in terms of expected number of backorders.

3.2. Description of Costs

The buyer incurs a cost r for each system failure incident and additionally a cost χ for each unit of system downtime. In expectation, this leads to the downtime cost of $\chi E[B|s]$. We note that even if the vendor maintains an inventory of spares and offers a replacement product to the buyer when a failure occurs, the buyer still incurs a disruption cost r. In the context of commercial airline operation, r represents, among other things, the cost of rescheduling flights that results from delays due to engine inspection and repair. The expected repair cost incurred to the vendor for each failure is denoted by M. Each unit of spare inventory costs c. To avoid trivial results we assume that $\chi \geq c$.

3.3. Endogenous Performance and Inventory Commitment

The inventory level of spares plays a significant role in the product maintenance setting. Spares substitute failed products and therefore help reduce product downtimes. This operational characteristic makes product performance partially endogenous, even though reliability is exogenous (we consider endogenous reliability in §6.4). We consider two cases with respect to inventory: verifiable and unverifiable. If the inventory level can be verified by the buyer, the vendor specifies it as part of contract terms (in RBC or PBC), fully expecting that the buyer will use this information when he makes a contract acceptance decision. Therefore, inventory level commitment is used as an additional signaling device in this case. On the other hand, if inventory level cannot be observed, it is not contractible since a contract based on unobserved variables cannot be enforced; the buyer has to rely entirely on the vendor's voluntary decision on inventory. This situation creates a moral hazard problem coupled with asymmetric information which leads to different dynamics, as we demonstrate in our analysis.

Inventory would be unverifiable if an audit of inventory is prohibitively costly or may not even be feasible. However, there do exist (costly) means to make inventory verifiable. For instance, CD Aviation Services, a Honeywell authorized service center, offers the SilverSky program which enables customers to track the progress of their maintenance or repair job with detailed status reports and pictures via secure Internet access anytime and from anywhere in the world, thereby making inventory verifiable (p. 18 in Adler et al. (2009)). Alternately, inventory can be made verifiable if it is maintained at the customer site, as is known to be done in the context of leased engines (Ray 2010). Thus, verifiability of inventory can be thought of as an attribute of the vendor-buyer relationship.

In general, for settings in which product warranties are used, another possible concern is the impact of shirking (or moral hazard) on the part of the buyer (Lutz 1989, Jain et al. 2011). We do not capture this type of opportunistic customer-behavior in our model. In the context of PBC for aircraft engines, we know that vendors monitor the health, performance, and usage of engines remotely and utilize a state-dependent payment scheme, thereby mitigating the potential for moral hazard on the part of the customer (p. 9 and 31 in Adler et al. (2009))

3.4. Description of Contracts

If the vendor offers RBC, she specifies the amount of fixed-fee and the share of the costs the buyer bears after each product failure incident. Thus, RBC charges the buyer for the repair cost incurred after each failure and reimburses her partially. If the vendor offers PBC, on the other hand, the vendor specifies the fixed-fee and the rate at which she will be penalized for product downtime.

A general transfer payment T from the buyer to the vendor, which subsumes RBC and PBC, consists of a fixed component w, in addition to resource-sharing components $\alpha \geq 0$ and $\beta \geq 0$, and performance-based components δ and v. The parameter α represents the buyer's share of the direct cost of repair and maintenance for each failure, while β represents the buyer's share of the spare inventory cost. The parameter δ is used to penalize buyer's inconvenience resulting from a system failure, while v is used to impose an additional penalty if the failure results in downtime due to insufficient spares (backorders). We summarize the contract parameters, either with the vector $\mathbf{C} = (w, \alpha, \beta, \delta, v, s)$ when inventory is observable and verifiable (and therefore contractible); or with vector $\mathbf{C} = (w, \alpha, \beta, \delta, v)$ when inventory is unverifiable. Therefore, the transfer payment can be represented as: $T(\mathbf{C}) = w + \beta cs + \alpha\mu M - vE[B|s] - \delta\mu r$.

We note that the term involving β is redundant since, if inventory is observable and verifiable, it can be folded under w; while if inventory is unverifiable then enforcing sharing of associated costs is not very meaningful. We also note that, from a mathematical perspective, contracting with δ is equivalent to allowing α to be negative while setting $\delta = 0$. Hence, we can rewrite the contract parameter vector as $\mathbf{C} = (w, \alpha, v, s)$ or (w, α, v), and the transfer payment as $T(\mathbf{C}) = w + \alpha\mu M - vE[B|s]$.

The maximum possible revenues the buyer would generate, assuming there is no disruption, is denoted by the constant R. The buyer's payoff can then be written as $U(\mathbf{C}) = R - T(\mathbf{C}) - \chi E[B|s] - \mu r$ or dropping the constant R, an analytically equivalent representation is $U(\mathbf{C}) = -T(\mathbf{C}) - \chi E[B|s] - \mu r$. The vendor decides the parameters in the transfer payment and also the inventory level for spares. Her payoff is $V(\mathbf{C}) = T(\mathbf{C}) - cs - \mu M$. For expositional convenience, going forward we will suppress the notation for the contract parameter vector, $\mathbf{C}$, and make it implicit whenever it does not cause confusion.

4. Benchmark Case: First-Best

The first-best treatment requires that all attributes, decisions and actions are completely observable and verifiable. We capture only the fixed-fee component, along with inventory specification, in the transfer payment, T, since, as it turns out, the outcome for either player cannot be improved upon by using any other form of transfer payment. The vendor's problem, which we use as the benchmark model that characterizes the first-best outcome will be $\max_{w,s\geqslant 0} V = w - cs - \mu M$, such that:

$$U = -w - \chi E(B|s) - \mu r \geqslant \theta. \tag{IR}$$

In the following proposition we provide the results from our analysis of the above optimization program.

PROPOSITION 1. *When the vendor's reliability and inventory level are observable and verifiable, the optimal contract specifies the following first-best decisions (w,s), for* $\chi \geq c$*:* $\overline{s} = F^{-1}(1 - \frac{c}{\chi})$, $\overline{w} = -\left(\chi E(B|\overline{s}) + \mu r + \theta\right)$.

All proofs can be found in the Appendix. The fixed-fee charged is high enough to extract all of the surplus from the buyer, and since there are no distortions or informational asymmetries it is not surprising that a fixed-fee and inventory specification suffices to extract all surplus from the buyer. Thus, we note that in the full information setting, since a fixed-fee contract is a special case of both RBC and PBC, the players are indifferent in their choice between the two.

5. The Informed Vendor

As discussed in the Introduction, the vendor has superior information about the failure distribution of the systems that it sells to the buyer. We model this by assuming that the vendor could be either of two types: H or L. Type H denotes the unreliable type of vendor, i.e., the likelihood of failure of the system is higher. By a similar token, type L denotes the reliable vendor, i.e., the likelihood of system failure is lower than that for the unreliable type. The corresponding failure distributions are G_H and G_L respectively. We assume that there is a strict first order stochastic dominance (FOSD) relationship between the two distributions, i.e., $G_H(x) < G_L(x), \forall x > 0$, such that $\mu_H > \mu_L$. The FOSD relationship captures the systematically lower risk of failure for the systems manufactured by the reliable type as opposed to the unreliable type. We assume that the buyer believes ex-ante that the vendor is of type H with probability $\pi > 0$. Further, we assume that this belief is *common knowledge*.

We note that on-order or pipeline inventory is an increasing function of the number of failures, therefore by Theorem 1.2.13 in Müller and Stoyan (2002), we conclude that F_H stochastically dominates F_L, i.e., $F_H(x) < F_L(x), \forall x > 0$. Our next result, which follows from Proposition 1, contrasts the contractual outcomes for the two types of vendors.

COROLLARY 1. *In the first-best setting, a reliable vendor achieves a higher payoff than the unreliable type, i.e.,* $\overline{V}_L > \overline{V}_H$*; and the reliable vendor chooses a lower inventory level than the unreliable vendor, i.e.,* $\overline{s}_L < \overline{s}_H$*.*

The above result confirms our intuition that the reliable type of vendor is better-off than the unreliable type when there is full information. Another inference from the details of the proof for the above corollary, is that the unreliable type has an incentive to mimic the reliable type, i.e., if the unreliable type could convince the buyer to accept the reliable type's first-best contract, then it would achieve a higher payoff than with her own first-best contract.

A natural question to ask is whether the reliable vendor does better on the availability performance metric, i.e., does contracting with the reliable vendor result in lower expected backorders: $E[B|s] = \int_s^\infty (1 - F(x))dx$? A sufficient condition for this to be true is:

$$\int_{F_L^{-1}(p)}^{\infty} (1 - F_L(x))\, dx \leq \int_{F_H^{-1}(p)}^{\infty} (1 - F_H(x))\, dx, \quad \forall p \in [0,1]. \tag{1}$$

It is easy to see this if we substitute the result from Proposition 1 in the above condition: $\overline{s}_\tau = F_\tau^{-1}(1 - c/\chi)$. This condition is the definition of the excess wealth order, also known as "right spread" order (see definition 3.C.1 in Shaked and Shanthikumar (2007)). If the failure distribution itself is Poisson, then assuming the excess wealth order on the failure distributions, G_L and G_H, is sufficient for condition (1) to hold (using Theorem 3.C.4 in Shaked and Shanthikumar (2007)).

Since the vendor has private information and also proposes the contract terms, the analysis of the interaction between the vendor and buyer can be represented as a signaling game in a Principal-Agent framework, in which the principal is the informed party (Maskin and Tirole 1992). The sequence of events is as follows:

1. Nature reveals to the vendor her type, $\tau \in \{L, H\}$.
2. Vendor offers contract terms (possibly type-contingent) to buyer.
3. Buyer updates its beliefs about vendor's type, and accepts or rejects the contract.
4. Vendor decides the inventory level of spares to be maintained; systems are utilized, failures occur, and repair and maintenance takes place; transfer payment is made by buyer and final payoffs are realized by both players.

In what follows, the notation $\sigma(L|\mathbf{C})$ denotes the buyer's updated belief that the vendor is of type L after observing the contract offer $\mathbf{C}$. For type $\tau \in \{L, H\}$, the expected payoff of the vendor of type τ under contract $\mathbf{C}$ are: $V_\tau = T_\tau - cs_\tau - \mu_\tau M$, where $T_\tau = w_\tau + \alpha_\tau \mu_\tau M - v_\tau E_\tau(B|s_\tau)$, while the buyer's expected payoff conditional on the vendor being of type τ is given by: $U_\tau = -T_\tau - \chi E_\tau(B|s_\tau) - \mu_\tau r$. Hence, the buyer's expected payoff can be written as: $U = \sigma(L|\mathbf{C})U_L + (1-\sigma(L|\mathbf{C}))U_H$.

It is typical to find multiple equilibria in the analysis of signaling games as the concept of perfect Bayesian equilibrium (PBE) does not place many restrictions on the off-equilibrium beliefs of the players. This feature has resulted in a fairly substantial literature on refinements of PBE, which impose restrictions on off-equilibrium beliefs in order to eliminate "unreasonable" beliefs. The equilibrium concept that we work with is PBE along with the most popular of these refinements — the "intuitive criterion" proposed by Cho and Kreps (1987).

Specifically, the "intuitive criterion" requires that off-equilibrium beliefs put zero weight on types that have no incentive to deviate, no matter what the buyer would conclude from observing the deviation. For our setting with two possible types of the vendor, an equilibrium contract, $\mathbf{C}$, which offers payoff $V_L(\mathbf{C})$ and $V_H(\mathbf{C})$ to the L and H-type vendor respectively, would fail the "intuitive criterion" if there exists a deviation (alternate contract, $\hat{\mathbf{C}}$), such that either of the following set of conditions hold:

(A1) The H-type vendor is always worse-off in the deviation, irrespective of the buyer's beliefs, as compared to her payoff in the proposed equilibrium: $\max_\sigma V_H(\hat{\mathbf{C}}) = V_H(\hat{\mathbf{C}}) < V_H(\mathbf{C})$. (A2) The L-type achieves a higher payoff in the deviation than in the proposed equilibrium: $V_L(\hat{\mathbf{C}}) > V_L(\mathbf{C})$. (A3) The participation constraint for the buyer is satisfied if he believes that the vendor is of the L-type with certainty: $U_L(\hat{\mathbf{C}}) \geq \theta$. Or such that:

(B1) The L-type vendor is always worse-off in the deviation, irrespective of the buyer's beliefs, as compared to her payoff in the proposed equilibrium: $\max_\sigma V_L(\hat{\mathbf{C}}) = V_L(\hat{\mathbf{C}}) < V_L(\mathbf{C})$. (B2) The H-type vendor achieves a higher payoff in the deviation than in the proposed equilibrium: $V_H(\hat{\mathbf{C}}) > V_H(\mathbf{C})$. (B3) The participation constraint for the buyer is satisfied if he believes that the vendor is of the H-type with certainty: $U_H(\hat{\mathbf{C}}) \geq \theta$.

We refer to a deviation satisfying A1-A3 as a *consistent low-failure separating deviation*, while a deviation satisfying B1-B3 is referred to as a *consistent high-failure separating deviation* (Lutz 1989). We now investigate our setting, with RBC and PBC arrangements, first for the case of verifiable inventory and then for unverifiable inventory.

5.1. RBC with Verifiable Inventory

We first study separating equilibria and then proceed to the analysis of pooling equilibria. In a separating equilibrium, different types of the informed party offer distinct contractual terms to the uninformed party, thereby leading to truthful disclosure of private information to the uninformed party in equilibrium. In a pooling equilibrium, all types of the informed party offer the same contract terms to the uninformed party, thereby preventing signalling.

5.1.1. Separating Equilibria. The transfer payment from the buyer to the vendor comprises a fixed component (potentially type-contingent), w_τ, as well as a share (potentially type-contingent), $\alpha_\tau \geq 0$, of the direct cost of repair and maintenance that is incurred by the vendor. As we would like to focus on RBC in this section, we restrict the performance-based components of the contract to zero, i.e., $v_\tau = 0$. The payoff of the vendor of type $\tau \in \{L, H\}$ is: $V_\tau = T_\tau - cs_\tau - \mu_\tau M = w_\tau + \alpha_\tau \mu_\tau M - cs_\tau - \mu_\tau M = w_\tau - (1-\alpha_\tau)\mu_\tau M - cs_\tau$, while the payoff of the buyer, when the vendor is of type τ, is:$U_\tau = -T_\tau - \chi E_\tau(B|s_\tau) - \mu_\tau r = -w_\tau - \alpha_\tau \mu_\tau M - \chi E_\tau(B|s_\tau) - \mu_\tau r$.

We first analyze the separating equilibria for this game. All separating equilibria must satisfy the following participation (IR) and incentive compatibility (IC) constraints:

$$-w_L - \alpha_L \mu_L M - \chi E_L(B|s_L) - \mu_L r \geq \theta, \tag{IR\_L}$$

$$-w_H - \alpha_H \mu_H M - \chi E_H(B|s_H) - \mu_H r \geq \theta, \tag{IR\_H}$$

$$w_L - (1-\alpha_L)\mu_L M - cs_L \geq w_H - (1-\alpha_H)\mu_L M - cs_H, \tag{IC\_L}$$

$$w_H - (1-\alpha_H)\mu_H M - cs_H \geq w_L - (1-\alpha_L)\mu_H M - cs_L. \tag{IC\_H}$$

The first constraint (IR_L) ensures that the buyer dealing with the reliable vendor makes at least his reservation value and therefore would willingly participate. The second constraint (IR_H) ensures participation when the vendor is of the unreliable type. The third and fourth constraints ((IC_L) and (IC_H) respectively) ensure that the separating equilibrium is indeed truth-telling, i.e., neither the reliable type nor the unreliable type is better-off mimicking the other.

We note the RBC exhibits a warranty-scheme like structure, i.e., a lower value of α_τ suggests a greater willingness on the part of the vendor to bear the financial burden associated with system failures. Do RBCs offer an advantage to the reliable type of vendor in her ability to credibly signal her type by agreeing to set a lower α than the unreliable type?

We now show that under RBC signalling is possible, however: (i) it is not possible for both types of the vendor to simultaneously recover first-best rents in a separating equilibrium; (ii) to achieve economic efficiency, the reliable vendor has to surrender rent to the buyer.

Proposition 2. *With RBC and verifiable inventory, there exist multiple separating equilibria that allow the vendor to signal her type. Each of these PBE exhibits the following properties:*

a) The unreliable type of the vendor recovers her first-best payoff, i.e., $V_H^* = \overline{V}_H$.

b) The reliable type of the vendor does better than the unreliable type, but does not recover her first-best payoff, i.e., $V_H^* < V_L^* < \overline{V}_L$.

c) The equilibria are characterized by the strategies $(w_L^*, \alpha_L^*, s_L^*)$ *and* $(w_H^*, \alpha_H^*, s_H^*)$ *for the reliable and unreliable type of vendor respectively, such that (IR_H) and (IC_H) are binding, and*

$$0 = \alpha_L^* \le \alpha_H^*,\ s_H^* = \overline{s}_H,\ w_H^* = -\theta - \mu_H r - \chi E_H(B|\overline{s}_H) - \alpha_H^* \mu_H M,$$

$$\max\{0, s^m\} \le s_L^*, \overline{s}_L \le s^M,\ w_L^* = -\theta - \mu_H r - \chi E_H(B|\overline{s}_H) + c(s_L^* - \overline{s}_H),$$

where s^m *and* s^M *are the two roots of the equation:* $cs + \chi E_L(B|s) = (\mu_H - \mu_L)r + \chi E_H(B|\overline{s}_H) + c\overline{s}_H$.

d) A belief structure for the buyer, that supports these equilibria, is: $\sigma(L|(w_L^*, \alpha_L^*, s_L^*)) = 1$, $\sigma(L|(w, \alpha, s)) = 0$, *if* $(w, \alpha, s) \ne (w_L^*, \alpha_L^*, s_L^*)$.

e) The economically efficient and Pareto optimal separating equilibria have $s_L^* = \overline{s}_L$.

Thus, we observe that in any separating equilibrium the reliable vendor will offer full warranty ($\alpha_L = 0$), but this is not necessarily the case for the unreliable vendor. Further, there exist multiple equilibria with $s_L^* \in [\max\{0, s^m\}, s^M]$. In these equilibria the reliable vendor surrenders rent to the buyer in order to signal her type. The choice of inventory level, s_L^*, does not affect the payoff of the vendor but only that of the buyer.

While the inability of the efficient type to recover first-best payoffs is common in the signaling literature (e.g., Spence 1973), more interestingly in our setting, this inability does not necessarily imply inefficiency across the supply chain. Economic efficiency requires that the inventory level, s_τ, maintained by each of the two types of the vendor, is equal to the first-best inventory level ($\overline{s}_H$ and $\overline{s}_L$ for the H and L-type respectively). Since $\max\{0, s^m\} \le \overline{s}_L \le s^M$, therefore, there do exist separating equilibria with $s_L^* = \overline{s}_L$. These particular equilibria result in the maximal benefit to the buyer and are economically (and Pareto) efficient. Note that, a continuum of such economically efficient equilibria are possible, each with a different value for $\alpha_H^* \ge 0$, but resulting in exactly the same payoffs for all player-types.

From the buyer's perspective, any equilibrium in which he is left with positive surplus is more desirable than zero surplus. However, we note that the Pareto optimal equilibrium, which is often argued to be the likely outcome in a game with multiple equilibria, also leaves the buyer with the maximal surplus.

So why is the reliable vendor (L-type) not able to recover first-best rents in any separating equilibrium with RBC? The reason is as follows. The vendor simultaneously optimizes her profits and deters mimicking by trading off the upfront fixed-fee she receives with the costs of offering a warranty and maintaining a specified level of inventory. The reliable type of vendor could have potentially differentiated herself from the unreliable type by offering a greater warranty (lower α) while maintaining first best inventory ($\overline{s}_L$). Further, in order to achiever first best rents, she would demand a high-enough fixed-fee that not only compensates her for the higher warranty she offers but also extracts all rents from the buyer. However, a higher fixed-fee makes it more attractive for the unreliable type of vendor to mimic, i.e., hold the inventory of the L-type and offer the L-type's high warranty. Clearly, the contract which the unreliable vendor finds most costly to mimic is one in which the reliable type offers a full warranty, i.e., $\alpha_L^* = 0$. However, we show that even under full warranty, the corresponding fixed-fee that allows the reliable type to extract first best rents is "too high". More specifically, the unreliable vendor will have an incentive to mimic as this high fixed-fee more than compensates for the increased warranty costs. Thus, in order to signal, the reliable type charges a lower fixed-fee that makes mimicking unattractive. In doing so she surrenders rents to the buyer.

5.1.2. Pooling Equilibria. We now turn our attention to the analysis of pooling equilibria using RBC. In a pooling equilibrium, both types of the vendor offer the same contract to the buyer. Hence, the buyer learns no new information about the vendor's type upon observing the offered contract. In other words, the buyer's posterior belief (after the contract offer) remains the same as his prior. Any pooling equilibrium, (w_p, α_p, s_p), must satisfy the buyer's participation constraint, i.e., $-w_p - \alpha_p \mu_p M - \chi E_p(B|s_p) - \mu_p r \geq \theta$, where $E_p(\cdot) = \pi E_H(\cdot) + (1-\pi)E_L(\cdot)$ and $\mu_p = \pi\mu_H + (1-\pi)\mu_L$. We proceed with our formal characterization of the pooling equilibria.

Proposition 3. *With RBC and verifiable inventory, pooling equilibria exist with $\alpha_p = 0$. In particular, the pooling equilibrium that results in the highest possible payoff to the vendor, is unique and exhibits the following properties:*

a) The payoff of the unreliable vendor, V_H^p, is greater than her first-best payoff, i.e., $V_H^p > \overline{V}_H$.

b) The payoff of the reliable vendor, V_L^p, is less than her first-best payoff, but greater than her payoff in a separating equilibrium, i.e., $V_L^* < V_L^p < \overline{V}_L$.

c) The strategy $(w_p^*, 0, s_p^*)$ is such that $w_p^* = -\chi E_p(B|s_p^*) - \mu_p r - \theta$, $s_p^* = F_p^{-1}\left(1 - \frac{c}{\chi}\right)$, where $F_p(.) = \pi F_H(.) + (1-\pi)F_L(.)$. Also, $\overline{s}_L < s_p^* < \overline{s}_H$.

d) A belief structure (consistent with Bayes' rule) for the buyer, that supports this equilibrium, is: $\sigma(L|(w_p^*, 0, s_p^*)) = 1-\pi$, $\sigma(L|(w, \alpha, s)) = 0$, if $(w, \alpha, s) \neq (w_p^*, 0, s_p^*)$.

The above proposition yields a number of interesting insights. We first observe that only a full warranty is offered in equilibrium. If this were not the case, then the reliable type vendor would find it profitable to deviate by offering greater warranty (lower α) coupled with a higher upfront fixed-fee, without affecting the buyer's payoff. Further, within the class of pooling equilibria with full warranty ($\alpha = 0$), the vendor's most preferred equilibrium is such that no consistent deviation is possible. Irrespective of her type, the vendor is better-off in this equilibrium than in any separating equilibrium. However, it is noteworthy that the buyer is better off in a separating equilibrium than in a pooling equilibrium. Thus, we can expect differing perspectives between the vendor and buyer regarding the relative attractiveness of separating versus pooling equilibria with RBC.

From a technical perspective, the pooling equilibrium described in Proposition 3 is interesting. While it is generally the case that pooling equilibria are eliminated on application of the "intuitive criterion" (Cho and Kreps 1987), we find that it not only survives the refinement, but both types of the vendor are better-off than in any separating equilibrium. Another rare example of such a result can be found in Proposition 4 of Lutz (1989).

It is also clear that *all* pooling equilibria result in economic inefficiency. This is because economic efficiency requires the reliable and unreliable types of the vendor to choose $\overline{s}_L$ and $\overline{s}_H$ respectively, while they choose the same inventory level in any pooling equilibrium. In contrast, we have already shown that there do exist separating equilibria that are economically efficient. We note that with RBC and verifiable inventory, neither separating nor pooling equilibria allow both types of the vendor to simultaneously recover their first-best payoffs.

5.2. PBC with Verifiable Inventory

The transfer payment from the buyer to the vendor comprises a fixed component (potentially type-contingent), w_τ, as well as a penalty rate (potentially type-contingent), v_τ, applied to every backorder. This reflects the situation where the vendor is penalized for downtime which is proportional to the number of backorders. In order to focus on the performance-based aspects of the contracts we set $\alpha = 0$. The payoff of the vendor of type $\tau \in \{L, H\}$ is $V_\tau = T_\tau - cs_\tau - \mu_\tau M = w_\tau - v_\tau E_\tau(B|s_\tau) - cs_\tau - \mu_\tau M$; while the payoff of the buyer, when the vendor is of type τ, is: $U_\tau = -T_\tau - \chi E_\tau(B|s_\tau) - \mu_\tau r = -w_\tau + (v_\tau - \chi)E_\tau(B|s_\tau) - \mu_\tau r$.

We begin with the analysis of separating equilibria. All such equilibria must satisfy the following participation (IR) and incentive compatibility (IC) constraints:

$$-w_L + (v_L - \chi)E_L(B|s_L) - \mu_L r \geq \theta, \tag{IR\_l}$$

$$-w_H + (v_H - \chi)E_H(B|s_H) - \mu_H r \geq \theta, \tag{IR\_h}$$

$$w_L - v_L E_L(B|s_L) - cs_L - \mu_L M \geq w_H - v_H E_L(B|s_H) - cs_H - \mu_L M, \tag{IC\_l}$$

$$w_H - v_H E_H(B|s_H) - cs_H - \mu_H M \geq w_L - v_L E_H(B|s_L) - cs_L - \mu_H M. \tag{IC\_h}$$

We now demonstrate that, when inventory is verifiable, PBC indeed outperforms RBC from the vendor's perspective.

PROPOSITION 4. *a) With PBC and verifiable inventory, there exist multiple separating equilibria that allow each type of the vendor to credibly signal her quality and achieve first-best payoff, i.e.,* $V_H^* = \overline{V}_H$ *and* $V_L^* = \overline{V}_L$.

b) These PBE are characterized by the strategies (w_L^*, v_L^*, s_L^*) *and* (w_H^*, v_H^*, s_H^*) *for the L-type and H-type vendor respectively, such that (IR_l) and (IR_h) are binding, and:*

$$w_L^* = -\theta - \mu_L r + (v_L^* - \chi)E_L(B|\overline{s}_L); s_L^* = \overline{s}_L, \tag{2}$$

$$w_H^* = -\theta - \mu_H r + (v_H^* - \chi)E_H(B|\overline{s}_H); s_H^* = \overline{s}_H; \tag{3}$$

where:

$$\begin{aligned} v_H^* \left[E_H(B|\overline{s}_H) - E_L(B|\overline{s}_H)\right] &\leq \chi[E_H(B|\overline{s}_H) - E_L(B|\overline{s}_L)] + (\mu_H - \mu_L)r + c(\overline{s}_H - \overline{s}_L) \\ &\leq v_L^* \left[E_H(B|\overline{s}_L) - E_L(B|\overline{s}_L)\right]. \end{aligned} \tag{4}$$

A belief structure for the buyer, that supports these equilibria, is: $\sigma(L|(w_L^*, v_L^*, s_L^*)) = 1$, $\sigma(L|(w, v, s)) = 0$, *if* $(w, v, s) \neq (w_L^*, v_L^*, s_L^*)$.

c) With PBC and verifiable inventory, pooling is not possible as an equilibrium outcome.

Given that first-best payoffs are achieved, we establish that PBC ameliorates the inefficiencies associated with asymmetric information. The reason the vendor is able to credibly and efficiently signal her type with PBC is the ability of the reliable type to promise a higher penalty rate (in exchange for a higher upfront fixed-fee payment) vis-à-vis the unreliable type. However, it is noteworthy that even though both types of the vendor recover first-best payoffs and maintain inventory levels $\overline{s}_L$ and $\overline{s}_H$, from (4) we know that it is not essential that $v_L^* = v_H^* = \chi$ in every PBE, i.e., the penalty rate v_τ need not necessarily reimburse the buyer for the entire loss arising from a backorder. This observation will be of interest when we discuss the results of the next section on unverifiable inventory. Further, a special case of the possible separating equilibria involves $v_H^* = 0$ and $v_L^* > 0$, i.e., the unreliable vendor effectively offers RBC, while the reliable vendor offers PBC. Next, we note that none of the candidate pooling equilibria survive refinement using the "intuitive criterion".

We end this section by pointing out that the form of PBC we have chosen to model, i.e., penalty on backorders, is not the only form that results in first-best outcomes. An equivalent outcome could be obtained by allowing the α term in RBCs to be negative. This would essentially result in an alternate formulation for PBC since a negative α implies that a penalty is imposed on the vendor for every instance of failure. We have verified that such a contract also results in first-best outcomes but do not report this result for the sake of brevity. More importantly, our choice of the form of PBC is motivated by the extant literature and standard industry practice.

5.3. PBC with Unverifiable Inventory

We now extend our analysis to the case in which the spare products inventory levels maintained by the vendor are not observable or verifiable by the buyer. We do not formally analyze the case of RBC with unverifiable inventory, for the following reason. Even though it is feasible to have a resource-based contract only on expenditure incurred on repair and maintenance, i.e., on $\mu_\tau M$, we do not report our formal analysis of this case since it is easy to verify that once such a contract is signed, it would provide the vendor with no incentive to maintain costly inventory, i.e., $s_L^* = s_H^* = 0$. This would result in substantial inefficiencies. In the interests of space we refrain from reporting further details. Further, we note that this contract type is a special case of the contract form discussed in §5.3.2.

5.3.1. Performance in terms of Backorders only: Recall that in the case of verifiable inventory, the vendor was able to use the performance-based component, v_τ, of the contract to credibly signal the quality of her engines and thus extract all rents. When inventory is not contractible, the contract needs to send a credible signal and at the same time provide incentives for the vendor to keep a sufficient amount of inventory. These two conflicting objectives prevent the vendor from extracting all rents. Our next proposition formalizes this intuition. For part b) of the next result, in addition to assumption of stochastic dominance between the number of failures we will also make the assumption that the failures follow the excess wealth order of equation (1). This condition in necessary to uniquely characterize the payoffs in the second best contract.

PROPOSITION 5. *With PBC on backorders only, and unverifiable inventory:*

a) In any separating equilibria it is not possible for both types of the vendor to simultaneously recover their first-best payoffs.

b) If the failure distributions satisfy the relationship in (1), then separating equilibria always exist with the following contractual parameters: $v_H^* = \chi$, $w_H^* = -\theta - \mu_H r$, $w_L^* = -\theta - \mu_L r + (v_L^* - \chi)E_L[B|s_L(v_L^*)]$ *and* v_L^* *is the unique solution of:*

$$\chi E_H(B|\bar{s}_H) - v_L E_H(B|s_H(v_L)) + (v_L - \chi)E_L(B|s_L(v_L)) + c\,(\bar{s}_H - s_H(v_L)) + (\mu_H - \mu_L)r = 0. \quad (5)$$

Further, $v_L^* \in (\chi, \infty)$*. The inventory decisions* $s_\tau(v)$*, where* $\tau \in \{L, H\}$ *and* v *is the performance based penalty, are characterized by* $s_\tau(v) = F_\tau^{-1}\left(1 - \frac{c}{v}\right)$*. A belief structure for the buyer, that supports these equilibria, is:* $\sigma(L|(w_L^*, v_L^*)) = 1$*,* $\sigma(L|(w, v)) = 0$*, if* $(w, v) \neq (w_L^*, v_L^*)$*.*

c) With PBC on backorders only, and unverifiable inventory, pooling is not possible as an equilibrium outcome.

The above proposition describes a second-best contract in which the outcome is once again similar to that in job-market signaling (Spence 1973), i.e., the efficient type sacrifices some rent in order to signal her type. Further, since $v_L^* > \chi$, we can conclude that $s_L^* > \overline{s}_L$, or that the reliable vendor overinvests in inventory. This happens because the reliable vendor is willing to take a higher penalty on backorders in order to signal and differentiate itself from the unreliable vendor. However, in order to counterbalance this additional exposure, she decides to maintain a higher inventory level of spares so that the expected backorders go down. Since spares are costly this results in some loss of value for the reliable vendor and it cannot recover first-best. Next, we note that none of the candidate pooling equilibria survive refinement using the "intuitive criterion".

Our analysis leads us to the obvious next question. Is there a simple contractual remedy that can help alleviate the economic inefficiency engendered in this setting? Perhaps contracting on additional dimensions of performance, other than backorders, introduces the required flexibility to get around this problem. A desirable feature of any proposed contract is its ease of implementation. This is exactly what we explore in the next section in which we allow contracting on reliability, or every instance of unscheduled maintenance, in addition to backorders.

5.3.2. Performance in terms of Backorders and Inconvenience Cost: The transfer payment from the buyer to the vendor comprises a fixed component, w_τ, as well as a penalty rate, v_τ, applied to every backorder. Additionally, there is a penalty rate, α_τ, associated with every instance of failure (inconvenience). Recall that in §3.4 we had established that penalizing the vendor for inconvenience was mathematically equivalent to choosing a negative α_τ. In the following analysis we impose no sign-restriction on α_τ. The payoff of the vendor of type $\tau \in \{L, H\}$ is: $V_\tau = T_\tau - cs_\tau - \mu_\tau M = w_\tau + \alpha_\tau \mu_\tau M - v_\tau E_\tau(B|s_\tau) - cs_\tau - \mu_\tau M$, while the payoff of the buyer, when the vendor is of type τ, is: $U_\tau = -T_\tau - \chi E_\tau(B|s_\tau) - \mu_\tau r = -w_\tau - \alpha_\tau \mu_\tau M + (v_\tau - \chi) E_\tau(B|s_\tau) - \mu_\tau r$. Once again, we commence with the analysis of separating equilibria.

PROPOSITION 6. *a) With PBC on backorders and delay, and unverifiable inventory, there exist separating equilibria. Moreover, in each of these PBE, both types of the vendor extract all rents from the buyer and achieve first-best, and therefore economic efficiency:* $v_L^* = v_H^* = \chi$, $\alpha_L^* \leq -\frac{r}{M} \leq \alpha_H^*$; $\alpha_L^* < \alpha_H^*$, $w_L^* = -(\alpha_L^* M + r)\mu_L - \theta$; $w_H^* = -(\alpha_H^* M + r)\mu_H - \theta$, $s_L^* = \overline{s}_L$; $s_H^* = \overline{s}_H$. *A belief structure for the buyer, that supports these equilibria, is:* $\sigma(L|(w_L^*, \alpha_L^*, v_L^*)) = 1$; $\sigma(L|(w, \alpha, v)) = 0$, *if* $(w, \alpha, v) \neq (w_L^*, \alpha_L^*, v_L^*)$.

b) With PBC on backorders and delay, and unverifiable inventory, pooling is not possible as an equilibrium outcome.

This contract works because it delineates the signaling from the moral hazard problem. The performance-based component on reliability (α) does the signaling while the performance-based component on backorders (v) gives the perfect incentive to keep the right amount of inventory.

Finally, we note that none of the candidate pooling equilibria survive refinement using the "intuitive criterion".

In this sub-section, we have established that a more flexible PBC, than the one currently used in industry, would potentially lead to economic efficiency even with unverifiable inventory. We believe that contracting on both availability and reliability is one promising and practical way of achieving this goal. At first glance, this might appear counter-intuitive from the vendor's perspective, since willingness to offer compensation for every instance of unscheduled maintenance, in addition to a penalty for backorders, suggests a worse outcome for the vendor. However, as it turns out, the flexibility afforded by contracting on an additional dimension of performance actually benefits the vendor without hurting the buyer, i.e., it is Pareto improving.

Additionally, we note that, the contract form that we study in this sub-section subsumes the RBC as a special case. Recall that in equilibrium, the performance-based components $v_L^* = v_H^* = \chi$. Thus, clearly RBC contracts do not suffice. Moreover, we find that $\alpha_L^* < 0$, implying that a contract that is a simple hybrid of RBC and of PBC only on backorders is inadequate for restoring efficiency.

6. Discussion

Some issues in this paper merit a more detailed discussion: namely the issues of practical significance of our results, equilibrium selection, endogenous repair lead time, and endogenizing reliability via up-front investment in R&D. We also discuss avenues for future work.

6.1. Illustrative Numerical Example

The analysis presented in §5 demonstrates the signaling properties of RBCs and PBCs from a theoretical perspective. However, the question remains as to whether these contracts are of practical significance. In this section we present a numerical study which uses figures from the commercial jet-engine industry, summarized in Table 6.1, to demonstrate that this is indeed the case. The chosen unit of analysis is one month as payments between airlines and vendors are typically exchanged monthly. In this numerical example the buyer's outside option is normalized to zero and his ex-ante belief that the vendor is of H-type is set to $\pi = 0.5$. Payoffs reported are negative as we focus only on the cost side. As shown in figure 1, when the H-type's failure rate is 50% higher than L-type's (i.e. $\mu_H/\mu_L = 1.5$) the gap between the first-best revenues is over \$2 million per month. Evidently, being able to signal and recover first-best rents, something only achievable with PBC contracts, is of significant value to the vendor.[4] We also note that the PBC contract based on backorders (§5.3.1), which is used in practice, destroys between 5%-15% of value for the L-type vendor. This value can be recovered by using the PBC on availability and reliability (§5.3.2). It is worth noting

[4] The vendor's payoff in PBC seperating equilibria is not displayed as it coincides with first-best payoffs.

	Definition	Value	Source
χ	Backorder cost	\$2,000,000 per month	Estimated based on revenue per aircraft figures reported by airline-financials.com, an independent airline industry consulting firm.
c	Cost per spare	\$70,000 per month	Estimated based on engine lease-rental rates (Ray 2010) and cost of a spare engine (Adler et al. 2009).
$1/\mu_L$	Expected time between failures L-type vendor	2-5 years	Range reported in Guajardo et al. (2011).
$1/\mu_H$	Expected time between failures H-type vendor	2 years	Lower end of range reported in Guajardo et al. (2011).
r	Inconvenience cost	\$175,000	Engine replacement time $\sim$ 2 days; charged at rate of \$61 per minute of delay (Ramdas et al. 2011).
N	Number of engines	100	Typical order size of a large airline.
M	Cost per unscheduled maintenance	\$800,000	Estimated based on industry expert inputs and consistent with figures reported in Hopper (1998).

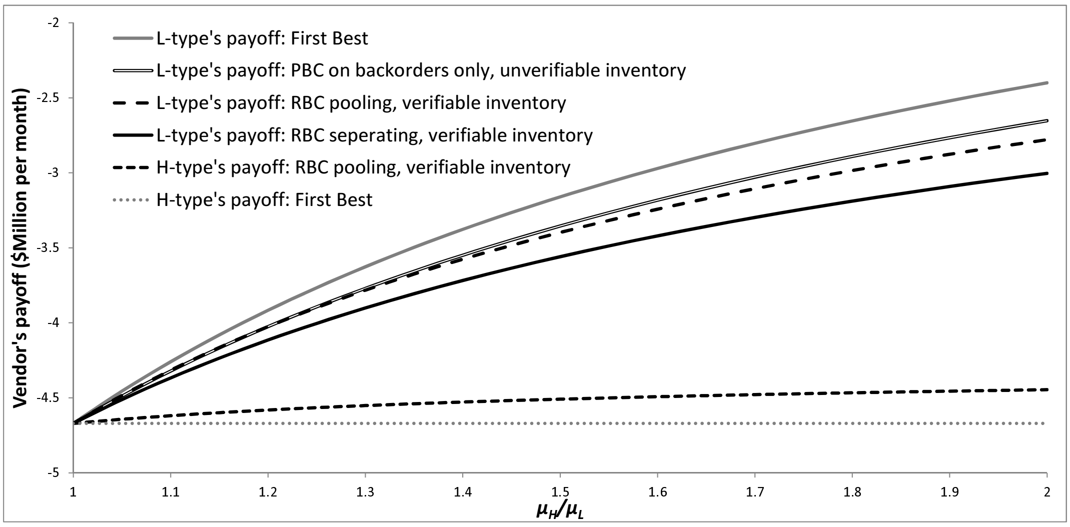

Figure 1 Results of numerical study

that the RBC separating equilibrium of §5.1.1 can leave significant rents with the buyer. These can be as much as the difference between the L-type's payoff in the RBC separating equilibrium and her first-best rents (which is approximately \$1 million per month when $\mu_H/\mu_L = 1.5$).

6.2. Multiple Equilibria

As noted in §5, it is common to encounter multiple equilibria in signaling games. We have conducted a rigorous analysis using the "intuitive criterion" as a refinement to narrow down the set of possible equilibria. We note that our analytical treatment of RBC with verifiable inventory identifies both separating and pooling as possible equilibrium outcomes. Further, we note that either type of equilibrium results in some appealing features — the separating equilibrium can be economically efficient; while both types of the vendor are better-off in the pooling equilibrium — and therefore neither of them appears nonsensical and an obvious candidate for elimination. We also lean towards the idea of appealing to the specific context to resolve the equilibrium selection issue. For instance, *if* some bargaining power is ascribed to the buyer, by modifying the sequence of events such that first step is for the buyer to choose the contract type to be used, before the vendor proposes the terms of the contract; then this "powerful" buyer would choose RBC and influence the play of game towards the separating equilibrium in which he is left with surplus.[5] In contrast, the buyer obtains zero surplus in the equilibrium with PBC.

6.3. Endogenous Repair Lead Time

In this research we have made the assumption that the repair lead time for products is exogenously specified. In practice, it might be possible for the vendor to shirk on turnaround time for repair since the required effort is costly, thereby making lead time endogenous. We now discuss conditions under which the insights from our analysis are robust to the assumption of exogenous repair lead time. For the case of unverifiable inventory, as per the flexible PBC described in Proposition 6, the vendor fully internalizes the economic costs of a backorder, i.e., $v_\tau = \chi$, for $\tau \in \{H, L\}$. Since the vendor is the residual claimant in a PBC arrangement, she will have no incentive to shirk on repair effort. On the other hand, for the case of verifiable inventory, we have described a software solution — SilverSky program — in §3.3, which enables the buyer to track the physical location and state of repair of a product in real-time, thereby considerably limiting the scope of shirking on the vendor's part.

6.4. Modeling R&D Investment

As yet, we have not formally modeled the decision regarding R&D investment in engine technology. If we assume that the outcome of R&D efforts (i.e., investment in engine reliability) is stochastic and ex-post unobservable to the buyer, then the overall game lasts for two periods. Signaling would occur in the second period, while the R&D decision would be made in the first period, in a fashion similar to Daughety and Reinganum (1995). In order to formalize these notions, assume that in the first period the vendor is faced with a binary decision of whether or not to invest in an R&D project that could result in an engine of low reliability with probability π and high reliability with probability $1-\pi$. This distribution is common knowledge. Also assume that the outcome of the R&D efforts are unobservable to the buyer and therefore his ex-post beliefs are the same as his ex-ante beliefs. The lump-sum expenditure associated with the project is ζ.[6] If the second period contractual arrangement is PBC based only on availability then the vendor would invest as long as her expected payoff from investing is greater than the cost: $\pi\overline{V}_H + (1-\pi)V_L^* \geq \zeta$. Here $\overline{V}_H$ and V_L^* are the equilibrium payoffs of the unreliable and reliable vendor respectively as per Proposition 5. However, with the more flexible PBC that contracts on both availability and reliability, the vendor would invest as long as: $\pi\overline{V}_H + (1-\pi)\overline{V}_L \geq \zeta$ (payoffs as per Proposition 6). Effectively, the threshold value of ζ above which the vendor will not invest in quality enhancing R&D goes up

[5] We know from our interactions with industry managers in the commercial aerospace sector that even though it is the vendor who proposes the contract terms, the airlines are often offered a choice between RBC and PBC.

[6] According to Mabert et al. (2006), it can cost as much as \$1.5 to \$2 billion to bring a new engine design to commercial viability.

in the second case since $\overline{V}_L > V_L^*$. As a result a larger number of proposed R&D projects will be taken up in the latter case. Therefore, being able to signal quality and extract full rents from the buyer has important beneficial implications for the incentive of the vendor to engage in R&D in the first place.

6.5. Avenues for Future Work

In arriving at our results we have abstracted away from some complexities. For instance, we have assumed that the demand for usage of systems seen by the buyer is fairly stable. However, this need not always be the case. Depending on economic conditions, demand seen by airlines might rise or fall, thereby resulting in recalibration of aircraft scheduling and usage. In particular, the mix of short-haul and long-haul flights might be changed by the airlines. This would have a knock-on effect on the requirement for spares. Since the lead times for procurement of spares is typically very long in the aerospace sector, such changes, if unanticipated, would lead the vendor to be worse-off with PBC (Mabert et al. 2006). Incorporating these considerations is a promising direction for future work. We have also assumed that the cost associated with delays, r, is known to both parties. However, this cost is likely to be a function of the operational capabilities of the buyer, and therefore private information to the buyer. Accounting for this feature could be another direction in which the research could be extended.

7. Conclusions

Our analysis reveals that PBC serves as a superior signaling device compared to RBC; an aspect that we show to be of practical significance and which has not been identified in the literature. We contrast the performance of RBC and PBC for the cases of verifiable and unverifiable inventory of spares. Our equilibrium results are summarized in Table 1. For the case of verifiable inventory, with RBC the reliable vendor has to surrender some rent to the buyer in order to credibly signal her reliability. Using a rigorous treatment of equilibrium refinements based on the "intuitive criterion", we show that even pooling equilibria with RBC exist (although they are never efficient). This implies that the vendor may intentionally hold back on revealing her product reliability via the contract terms, in order to avoid having to surrender rents to the buyer. On the other hand, with PBC, it is possible for the vendor to signal her reliability without the need to surrender rents to the buyer. The performance-penalty that is central to PBC, makes it prohibitively costly for the unreliable vendor to misrepresent the reliability of her product.

We observe that relative to the equilibrium outcome using PBC, the buyer is better-off in the separating equilibrium with RBC, while the unreliable vendor is better-off in the pooling equilibrium with RBC.[7] These results suggest conflicting perspectives between the vendor-types and

[7] There is anecdotal evidence to support our finding that from the buyer's perspective PBC is not necessarily desirable

Contract Type	Asymmetric Information with verifiable inventory	Asymmetric Information with unverifiable inventory
RBC	Efficient, but supplier does not achieve First-Best payoffs.	Inefficient (no inventory held)
PBC (availability)	EFB*	Inefficient & Second-Best
PBC (availability & reliability)	EFB	EFB

*EFB = Efficiency of supply-chain-wide payoffs and First-Best outcomes for the vendor are both attained.

Table 1 Summary of Results

buyer; and therefore offer a possible explanation for the continued co-existence of RBC and PBC in the commercial aerospace industry, in particular in the context of new engines. Essentially, we suggest that a "powerful" buyer and/or unreliable vendor would favor the use of RBC over PBC.

The case of unverifiable inventory gives rise to a setting in which asymmetric information is coupled with moral hazard. RBC is not very useful in this context as it provides no incentive whatsoever for the vendor to maintain any inventory after the contract is signed. In contrast, PBC not only provides the vendor with a strong incentive to maintain inventory via the backorder penalty, but it also allows effective signaling to take place compared to RBC. While PBC allows the vendor to signal her quality, first-best is not achieved if, as is common in practice, the only performance criterion that is assessed is availability. In order to deter mimicking, the reliable vendor will volunteer an inefficiently high backorder penalty, leading to overinvestment in inventory of spares. Significantly, we find that using PBC with a multivariate signal that draws a distinction between performance pertaining to availability (related to backorders) versus reliability (related to each instance of unscheduled maintenance), the vendor can once again signal her quality and achieve first-best, i.e., the signal is costless on the equilibrium path. Contracting on reliability would be a feasible and practical modification to current industry practices. Our interviews with industry practitioners reveal that it is also being considered actively as an option, going forward. This type of contract ameliorates economic inefficiency associated with asymmetric information. This could have further implications such as providing stronger incentives for R&D investment in engine reliability.

8. Appendix: Proofs

Proof of Proposition 1: The objective function is increasing in w, therefore the (IR) constraint must be binding at the optimal: $w = -(\chi E(B|s) + \mu r + \theta)$. We plug this back into the objective function and maximize wrt to inventory s to obtain $\overline{s} = F^{-1}(1 - \frac{c}{\chi})$ when $\chi \geq c$ and zero otherwise. The solution is unique as the objective is concave in s. $\square$

Before proceeding with the rest of the proofs we find it useful to first prove Lemma 1.

when there is asymmetric information. Based on a survey of private sector companies that outsource maintenance of complex equipment, GAO (2004) reports: "Company officials noted that in the absence of accurate and reliable information on system performance to establish a baseline for evaluating the cost-effectiveness of a performance-based contract for new systems, the risk of the negotiated prices being excessive is increased."

LEMMA 1. *For any value of* $u \geq c$, *it is the case that* $\phi(u) := u[E_L(B|s_L(u)) - E_H(B|s_H(u))] + c(s_L(u) - s_H(u)) < 0$, *where, for* $\tau \in \{L, H\}$ $s_\tau(u) = \arg\max_s [-uE_\tau(B|s) - cs] = F_\tau^{-1}\left(1 - \frac{c}{u}\right)$. *Furthermore, when the failure rate also satisfies the excess wealth order of equation 1, then* $\phi(u)$ *is non-increasing.*

Proof of Lemma 1: Since F_H stochastically dominates F_L, therefore for any $u > 0$ we have $s_L(u) \leq s_H(u)$. Furthermore, $\phi(u) = u[E_L(B|s_L(u)) - E_H(B|s_H(u))] + c(s_L(u) - s_H(u)) = u\int_{s_L(u)}^{s_H(u)} (1 - F_L(x))\,dx + u\int_{s_H(u)}^{\infty} (F_H(x) - F_L(x))\,dx + c(s_L(u) - s_H(u)) < u\int_{s_L(u)}^{s_H(u)} (1 - F_L(x))\,dx + c(s_L(u) - s_H(u)) \leq u\,(1 - F_L(s_L(u)))\,(s_H(u) - s_L(u)) + c(s_L(u) - s_H(u)) = 0$, where to get to the second line we use the stochastic dominance property of the failure rates which implies that $\int_{s_H}^{\infty} (F_H(x) - F_L(x))\,dx < 0$. For the third line we use the fact that $1 - F_L(x)$ is a non-increasing function, therefore the area under this curve in the interval $(s_L(u), s_H(u))$ is no greater than $(1 - F_L(s_L(u)))\,(s_H(u) - s_L(u))$. Finally we substitute $s_L(u)$ to show that the last line is zero.

Note that since the on-order inventory is an increasing convex function of the number of failures, then by Theorem 3.C.4 of Shaked and Shanthikumar (2007) we can conclude that if the failure distribution satisfies the excess wealth order then so does the distribution of on-order inventory. Given the definitions of $s_L(u)$ and $s_H(u)$, it follows that $\int_{s_L(u)}^{\infty} (1 - F_L(x))\,dx \leq \int_{s_H(u)}^{\infty} (1 - F_H(x))\,dx$, or $E_L(B|s_L(u)) \leq E_H(B|s_H(u))$. Taking the derivative of $\phi(u)$ with respect to u gives $\phi'(u) = [E_L(B|s_L(u)) - E_H(B|s_H(u))] \leq 0.\square$

Proof of Corollary 1: In the full information case, the buyer's participation constraint is tight in equilibrium. Therefore, the payoff of the vendor of type $\tau \in \{H, L\}$ is $\overline{V}_\tau = -\theta - \chi E_\tau(B|\overline{s}_\tau) - c\overline{s}_\tau - \mu_\tau(r + M)$, where the inventory is given by $\overline{s}_\tau = F_\tau^{-1}\left(1 - \frac{c}{\chi}\right)$. Then because of the stochastic dominance relationship between $F_H(.)$ and $F_L(.)$ we conclude that $\overline{s}_H > \overline{s}_L$. Further, $\overline{V}_H - \overline{V}_L = \chi[E_L(B|\overline{s}_L) - E_H(B|\overline{s}_H)] + c(\overline{s}_L - \overline{s}_H) + (\mu_L - \mu_H)(r + M) = \phi(\chi) + (\mu_L - \mu_H)(r + M)$, using Lemma 1 for $u = \chi$ and $\mu_L < \mu_H$, we conclude that: $\overline{V}_H - \overline{V}_L < 0$. $\square$

Proof of Proposition 2: In a separating equilibrium, if it exists, the vendor is able to credibly signal her type. Given that the H-type vendor has credibly communicated her type to the buyer, the best that she can do is to extract all the surplus by solving the following problem: $\max_{w_H, s_H, \alpha_H \geq 0} w_H - (1 - \alpha_H)\mu_H M - cs_H$, such that $-w_H - \alpha_H M\mu_H - \chi E_H(B|s_H) - \mu_H r \geq \theta$. The constraint will be binding at optimum (otherwise the vendor can increase the fixed-fee w_H and improve her payoff), therefore $w_H^* = -\alpha_H\mu_H M - \chi E_H(B|s_H) - \mu_H r - \theta$, and the objective becomes $\max_{s_H, \alpha_H \geq 0} -\chi E_H(B|s_H) - \mu_H(r + M) - \theta - cs_H$. This function does not depend on α_H and is concave in s_H, therefore, the optimal inventory to keep is equal to the first-best level, i.e., $s_H^* = \overline{s}_H$. The unreliable vendor makes her first-best payoff, $\overline{V}_H$.

Now consider the problem of the L-type vendor. If there exist no consistent separating deviations as per the "intuitive criterion", then the L type's contract must solve the following problem

$\max_{w_L,s_L,\alpha_L\geq 0} w_L-(1-\alpha_L)\mu_L M-cs_L$, subject to (IR_L): $-w_L-\alpha_L\mu_L M-\chi E_L(B|s_L)-\mu_L r\geq \theta$, (IC_H): $\overline{V}_H\geq w_L+\alpha_L\mu_H M-cs_L-\mu_H M$. Furthermore, for a separating equilibrium the L-type's contract needs to be incentive compatible, (IC_L): $w_L+\alpha_L\mu_L M-cs_L\geq \alpha_H(\mu_L-\mu_H)M-\chi E_H(B|\overline{s}_H)-\mu_H r-c\overline{s}_H-\theta$. Since the objective function is increasing in w_L and an increase in w_L cannot violate (IC_L), we have to conclude that either (IR_L) or (IC_H) is binding. We consider these possibilities in turn.

Case A: (IC_H) is binding. This implies $w_L=-\chi E_H(B|\overline{s}_H)-\mu_H r-\theta-c(\overline{s}_H-s_L)-\alpha_L\mu_H M$ and the optimization problem becomes: $\max_{s_L,\alpha_L\geq 0}-\chi E_H(B|\overline{s}_H)-\mu_H r-\theta-c\overline{s}_H-\mu_L M-\alpha_L(\mu_H-\mu_L)M$, subject to (IR_L): $\chi\left[E_H(B|\overline{s}_H)-E_L(B|s_L)\right]+c\left(\overline{s}_H-s_L\right)+(\mu_H-\mu_L)(\alpha_L M+r)\geq 0$ and (IC_L): $(\alpha_H-\alpha_L)(\mu_H-\mu_L)M\geq 0$. Note that (IC_L) implies that any feasible solution requires $0\leq\alpha_L\leq\alpha_H$. Furthermore, the objective function is independent of s_L and is decreasing in α_L. Starting with any feasible solution such that $\alpha_L>0$, decreasing α_L cannot violate (IC_L); and decreasing α_L does not violate (IR_L) as long as an appropriate inventory level, s_L is set. Therefore $\alpha_L=0$ at optimum, provided the following condition is satisfied $\chi\left[E_H(B|\overline{s}_H)-E_L(B|s_L)\right]+c\left(\overline{s}_H-s_L\right)+(\mu_H-\mu_L)r\geq 0$. This condition implies that s_L should satisfy, $\max\{0,s^m\}\leq s_L\leq s^M$, where s^m and s^M are the two roots of the equation $cs+\chi E_L(B|s)=(\mu_H-\mu_L)r+\chi E_H(B|\overline{s}_H)+c\overline{s}_H$. It is easy to verify that $\max\{0,s^m\}\leq\overline{s}_L<s^M$ by setting $u=\chi$ in Lemma 1, hence $\alpha_L^*=0$. Note that s^m could be negative depending on model parameters. The payoff of the reliable vendor is given by $V_L^*=-\chi E_H(B|\overline{s}_H)-c\overline{s}_H-\mu_H r-\mu_L M-\theta=\overline{V}_H+(\mu_H-\mu_L)M<\overline{V}_L$.

Case B: (IR_L) is binding. Solving the L-type's problem under this condition does not contain any further solutions.

The buyer's belief structure specified in the statement of the proposition ensures that neither type of the vendor has any incentive to deviate unilaterally from this equilibrium.□

Proof of Proposition 3: We first rule out pooling equilibria, $(w_p,\alpha_p>0,s_p)$, using conditions A1-A3 under the "intuitive criterion", i.e., by identifying a *consistent low-failure separating deviation*, $(w,\alpha\geq 0,s)$. We know that any pooling equilibrium satisfies (IR_p). Furthermore, condition A1 implies $w_p-cs_p+\alpha_p\mu_H M>w-cs+\alpha\mu_H M$, condition A2 implies $w_p-cs_p+\alpha_p\mu_L M<w-cs+\alpha\mu_L M$ and condition A3 implies $-w-\alpha\mu_L M-\chi E_L(B|s)-\mu_L r\geq\theta$. Set $w=w_p+\epsilon$, with $0<\epsilon\leq\alpha_p\mu_L M$, and $s=s_p$. The first two conditions above then imply: $0\leq\alpha<\alpha_p-\frac{\epsilon}{\mu_H M}$, $\alpha>\alpha_p-\frac{\epsilon}{\mu_L M}$. Note that since $\mu_H>\mu_L$, the RHS of the first inequality is larger than the RHS of the second. To show that the third condition is satisfied, we can replace θ on its RHS with the LHS of (IR_p). Or, it is sufficient to show that $-w-\alpha\mu_L M-\chi E_L(B|s)-\mu_L r\geq -w_p-\alpha_p\mu_p M-\chi E_p(B|s_p)-\mu_p r$, which can be rewritten as $\alpha\leq\alpha_p\left(\frac{\mu_p}{\mu_L}\right)-\frac{\epsilon}{\mu_L M}+\frac{\chi[E_p(B|s_p)-E_L(B|s_p)]+(\mu_p-\mu_L)r}{\mu_L M}$. Since $\frac{\mu_p}{\mu_L}>1$ and

$E_p(B|s_p) > E_L(B|s_p)$, therefore, we can conclude that the RHS of the inequality above is greater than $\alpha_p - \frac{\epsilon}{\mu_L M}$. Hence, it is possible to select α such that:

$$\alpha_p - \frac{\epsilon}{\mu_L M} < \alpha < \min\left[\alpha_p - \frac{\epsilon}{\mu_H M}, \alpha_p\left(\frac{\mu_p}{\mu_L}\right) - \frac{\epsilon}{\mu_L M} + \frac{\chi[E_p(B|s_p) - E_L(B|s_p)] + (\mu_p - \mu_L)r}{\mu_L M}\right]. \tag{6}$$

A deviation (w, α, s) such that $w = w_p + \epsilon$, where $0 < \epsilon \leq \alpha_p \mu_L M$; $s = s_p$; and α chosen so as to satisfy (6), rules out the proposed pooling equilibria.

However, not all pooling equilibria with $\alpha_p = 0$ are eliminated by the refinement imposed by the "intuitive criterion". Consider the vendor's most preferred candidate pooling equilibrium amongst the ones with $\alpha_p = 0$. It is determined by solving the following optimization program: $\max_{w_p, s_p}[w_p - cs_p]$ such that $-w_p - \chi E_p(B|s_p) - \mu_p r \geq \theta$. Clearly the constraint will be binding at optimal, therefore $w_p = -\chi E_p(B|s_p) - \mu_p r - \theta$ and using the definition of $E_p(.)$ we know that above objective is strictly concave in s_p, therefore it is maximized at $s_p^* = F_p^{-1}\left(1 - \frac{c}{\chi}\right)$, where $F_p(.) = \pi F_H(.) + (1-\pi)F_L(.)$. Due to the FOSD relationship between $F_H(.)$ and $F_L(.)$, it is easy to see then that $\overline{s}_L < s_p^* < \overline{s}_H$. By the same logic it has to be the case that $\mu_L < \mu_p < \mu_H$; $F_p(.)$ stochastically dominates $F_L(.)$; and $F_H(.)$ stochastically dominates $F_p(.)$. Using Lemma 1, we conclude that: $\phi_1(\chi) = \chi[E_L(B|\overline{s}_L) - E_p(B|s_p^*)] + c(\overline{s}_L - s_p^*) < 0$ and

$$\phi_2(\chi) = \chi[E_p(B|s_p^*) - E_H(B|\overline{s}_H)] + c(s_p^* - \overline{s}_H) < 0. \tag{7}$$

Then, if the τ type's payoff in the proposed pooling equilibrium $(w_p^*, 0, s_p^*)$ is denoted by V_τ^p:

$$V_H^p = -\chi E_p(B|s_p^*) - \mu_p r - \theta - cs_p^* - \mu_H M > -\chi E_H(B|\overline{s}_H) - \mu_H r - \theta - c\overline{s}_H - \mu_H M = \overline{V}_H, \tag{8}$$

$$V_L^p = -\chi E_p(B|s_p^*) - \mu_p r - \theta - cs_p^* - \mu_L M < -\chi E_L(B|\overline{s}_L) - \mu_L r - \theta - c\overline{s}_L - \mu_L M = \overline{V}_L. \tag{9}$$

If the buyer's belief structure in this proposed equilibrium is such that $\sigma(L|(w_p^*, 0, s_p^*)) = 1 - \pi$; $\sigma(L|(w, \alpha, s)) = 0$, if $(w, \alpha, s) \neq (w_p^*, 0, s_p^*)$, then there is no incentive for either type of vendor to deviate from the pooling equilibrium. To see this, note that (8) implies that the H type will be worse-off by deviating since the buyer's beliefs are such that it makes at most $\overline{V}_H$ in the deviation. It is also the case that the L type is worse-off in a deviation since (8) and (9) together imply that $V_L^p > \overline{V}_H + (\mu_H - \mu_L)M$. The RHS of this condition is also the maximum possible payoff the L type would make if it deviated from the pooling equilibrium and was treated as the H type by the buyer. Hence, there is no incentive to deviate.

This pooling equilibrium survives the "intuitive criterion". To see this, consider any candidate pooling equilibrium $(w_p, 0, s_p)$. For a deviation $(w, \alpha \geq 0, s)$, the conditions A1 and A2 per the "intuitive criterion" imply: $\frac{(w_p - cs_p) - (w - cs)}{\mu_L M} < \alpha < \frac{(w_p - cs_p) - (w - cs)}{\mu_H M}$. Since the $\mu_H > \mu_L$, the above condition can never be satisfied for $\alpha \geq 0$. If, $(w_p - cs_p) - (w - cs) > 0$, then $\frac{(w_p - cs_p) - (w - cs)}{\mu_L M} > \frac{(w_p - cs_p) - (w - cs)}{\mu_H M}$ leading to a contradiction. If, $(w_p - cs_p) - (w - cs) \leq 0$, then α is forced to be negative, and therefore not allowed. We have therefore ruled out a *consistent low-failure separating deviation*. We now consider the possibility of the existence of a *consistent high-failure separating deviation*. Take the Pareto dominant pooling equilibrium we identified earlier, $(w_p^*, 0, s_p^*)$, and a potential deviation, (w, α, s). Conditions B1 and B2 imply $\frac{(w_p - cs_p) - (w - cs)}{\mu_H M} < \alpha < \frac{(w_p - cs_p) - (w - cs)}{\mu_L M}$. This can be satisfied for a non-negative α if and only if $(w_p - cs_p) - (w - cs) = \epsilon > 0$. Further, this implies: $\epsilon < \alpha \mu_H M$. Condition B3, along with $(w_p - cs_p) - (w - cs) = \epsilon > 0$, imply: $\epsilon \geq \alpha \mu_H M + (\mu_H - \mu_p) r + cs + \chi E_H(B|s) - cs_p^* - \chi E_p(B|s_p^*)$. Since $cs + \chi E_H(B|s)$ is convex in s, and using the result in (7), we conclude that $cs + \chi E_H(B|s) - cs_p^* - \chi E_p(B|s_p^*) \geq c\overline{s}_H + \chi E_H(B|\overline{s}_H) - cs_p^* - \chi E_p(B|s_p^*) \geq 0$. Plugging this back into the previous inequality, we conclude $\epsilon > \alpha \mu_H M$, which is a contradiction. □

Proof of Proposition 4: We consider the possibility of recovering first-best rents in a separating equilibrium - (w_L^*, v_L^*, s_L^*) and (w_H^*, v_H^*, s_H^*). Since inventory is observable and verifiable it is straightforward to contract on its first-best levels - $\overline{s}_L$ and $\overline{s}_H$. However, the transfer payments need to adhere to the following incentive compatibility and participation constraints: (IR_l) (IR_h) (IC_l) and (IC_h) of page 17. Consider the following contract parameters $w_L^* = -\theta - \mu_L r + (v_L^* - \chi) E_L(B|\overline{s}_L)$, $w_H^* = -\theta - \mu_H r + (v_H^* - \chi) E_H(B|\overline{s}_H)$. Plugging the appropriate values in the LHS of (IR_l) and (IR_h), we obtain $-w_L^* + (v_L^* - \chi) E_L(B|\overline{s}_L) - \mu_L r = \theta + \mu_L r - (v_L^* - \chi) E_L(B|\overline{s}_L) + (v_L^* - \chi) E_L(B|\overline{s}_L) - \mu_L r = \theta$, $-w_H^* + (v_H^* - \chi) E_L(B|\overline{s}_H) - \mu_H r = \theta + \mu_H r - (v_H^* - \chi) E_H(B|\overline{s}_H) + (v_H^* - \chi) E_H(B|\overline{s}_H) - \mu_H r = \theta$. This implies that both types of the vendor recover their first-best outcomes, provided the incentive compatibility (IC) constraints are satisfied. We now check (IC_l). Plugging in the appropriate values, we obtain $v_H^* \left[E_H(B|\overline{s}_H) - E_L(B|\overline{s}_H)\right] \leq \chi [E_H(B|\overline{s}_H) - E_L(B|\overline{s}_L)] + (\mu_H - \mu_L) r + c(\overline{s}_H - \overline{s}_L)$. Similarly, (IC_h) implies $v_L^* \left[E_L(B|\overline{s}_L) - E_H(B|\overline{s}_L)\right] \geq \chi [E_H(B|\overline{s}_H) - E_L(B|\overline{s}_L)] + (\mu_H - \mu_L) r + c(\overline{s}_H - \overline{s}_L)$. The conditions above are satisfied for any: $v_H^* \left[E_H(B|\overline{s}_H) - E_L(B|\overline{s}_H)\right] \leq \chi [E_H(B|\overline{s}_H) - E_L(B|\overline{s}_L)] + (\mu_H - \mu_L) r + c(\overline{s}_H - \overline{s}_L) \leq v_L^* \left[E_H(B|\overline{s}_L) - E_L(B|\overline{s}_L)\right]$. Furthermore, such v_L^* and v_H^* always exist and are non-negative. To see this, note that the stochastic dominance relationship between the failure distributions implies: $[E_H(B|\overline{s}_H) - E_L(B|\overline{s}_H)] \geq 0$, $[E_H(B|\overline{s}_L) - E_L(B|\overline{s}_L)] \geq 0$ and $\chi [E_H(B|\overline{s}_H) - E_L(B|\overline{s}_L)] + (\mu_H - \mu_L) r + c(\overline{s}_H - \overline{s}_L) > 0$ due to Lemma 1 and $\mu_H > \mu_L$. The buyer's belief structure specified in the statement of the proposition ensures that neither type has any incentive to deviate unilaterally from this equilibrium.

Due to space considerations we provide a sketch of the proof that pooling equilibria are eliminated; a complete proof is available from the authors. We first use Conditions A1-A3, as specified under the description of the "intuitive criterion", to show that from all candidate pooling equilibria

(w_p, v_p, s_p), only those with $v_p \geq \chi + \frac{(\mu_P - \mu_L)r}{E_p(B|s_p) - E_L(B|s_p)}$ survive *consistent low-failure deviations* of the form $(w_p + \epsilon, v_p, s_p)$ and conditions B1-B3 to show that only those with $v_p \leq \chi + \frac{(\mu_H - \mu_P)r}{E_H(B|s_p) - E_p(B|s_p)}$ survive *consistent high-failure deviations* of the form $(w_p + \epsilon, v_p, s_p)$. We then show that these two inequalities together imply that the only candidate equilibria that survive are those with $v_p = \chi + \frac{(\mu_H - \mu_P)r}{E_H(B|s_p) - E_p(B|s_p)} = \chi + \frac{(\mu_P - \mu_L)r}{E_p(B|s_p) - E_L(B|s_p)}$. The second step uses again Conditions A1-A3 to identify *consistent low-failure deviations* of the form (w, v_p, s) to further rule out any equilibria that have inventory other than $s_p = \overline{s}_L$ and Conditions B1-B3 to identify *consistent high-failure deviations* of the form (w, v_p, s) to further rule out any equilibria that have inventory other than $s_p = \overline{s}_H$. Together these steps rule out all candidate separating equilibria.□

Proof of Proposition 5: We first note than when inventory is unverifiable it is impossible for both types of vendors to signal their type credibly. As in the proof of Proposition 2, in a separating equilibrium (if it exists) the H-type vendor achieves first best by setting $v_H^* = \chi$ and $w_H^* = -\mu_H r - \theta$ and for the L-type at least (IR_L) or (IC_H) need to be binding at optimum.

Case A: Assume that (IC_H) is binding, therefore $w_L(v_L) = -\theta - \mu_H r - \chi E_H[B|s_H(\chi)] - cs_H(\chi) + v_L E_H[B|s_H(v_L)] + cs_H(v_L)$, and the objective function of type L becomes $P(v_L) = v_L[E_H[B|s_H(v_L)] - E_L[B|s_L(v_L)]] + cs_H(v_L) - cs_L(v_L) + \nu(\chi) = -\phi(v_L) + \nu(\chi)$, where $\nu(\chi)$ is a function that does not depend on v_L and $\phi(x)$ is defined in Lemma 1. The (IR_L) constraint can then be written as $g(v_L) = \chi E_H[B|s_H(\chi)] - v_L E_H[B|s_H(v_L)] + (v_L - \chi)E_L[B|s_L(v_L)] + c(s_H(\chi) - s_H(v_L)) + (\mu_H - \mu_L)r \geq 0$, while the (IC_l) constraint as $\chi[E_L[B|s_L(\chi)] - E_H[B|s_H(\chi)]] + c(s_L(\chi) - s_H(\chi)) + v_L[E_H[B|s_H(v_L)] - E_L[B|s_L(v_L)]] + c(s_L(v_L) - s_H(v_L)) \geq 0$. This last constraint can be written as $\phi(\chi) - \phi(v_L) \geq 0$, where $\phi(x)$ is defined in Lemma 1. Since $\phi(x)$ is monotone decreasing in x (shown in Lemma 1) we can conclude that the objective function is increasing in v_L, therefore one of the remaining constraints (IR_l) or (IC_l) has to be binding (otherwise the L-type would be able to extract infinite rents). Furthermore, since $\phi(x)$ is monotone decreasing in x, (IC_L) is binding only when $v_L = \chi$ (and is always satisfied for $v_L > \chi$). Note that $v_L = \chi = v_H$ cannot be a solution as this is not a separating equilibrium. Therefore the solution must be defined at $g(v_L^*) = 0$ provided that $v_L^* > \chi$. Such a v_L exists and is unique because $g(x)$ is a continuous decreasing function as $\frac{d}{dv_L}g(v_L) = -\frac{c^2}{v_L^3}\frac{1}{f_L(s_L(v_L))}(v_L - \chi) - [E_H[B|s_H(v_L)] - E_L[B|s_L(v_L)]]$ which is always negative for $v_L > \chi$, with $g(\chi) = (\mu_H - \mu_L)r > 0$ and $\lim_{x\to\infty} g(x) = -\infty$. To see why the last limit is true note that $v_L[E_L[B|s_L(v_L)] - E_H[B|s_H(v_L)]] - cs_H(v_L) \leq -cs_H(v_L)$, therefore $g(x) \leq \chi E_H[B|s_H(\chi)] - \chi E_L[B|s_L(v_L)] + cs_H(\chi) - cs_H(v_L) + (\mu_H - \mu_L)r$ and $\lim_{x\to\infty} s_H(x) = \infty$, $\lim_{x\to\infty} E_L[B|s_L(x)] = 0$, therefore $\lim_{x\to\infty} g(x) \leq -\infty$.

Case B: (IR_L) is binding. Solving the L-type's problem under this condition does not contain any further solutions.

The buyer's belief structure that specified in the statement of the proposition ensures that neither type has any incentive to deviate unilaterally from this equilibrium. To show that pooling equilibria are eliminated we first use Conditions A1-A3, as specified under the description of the "intuitive criterion", to show that from all candidate pooling equilibria (w_p, v_p), only those with $v_p \geq \chi$ survive *consistent low-failure deviations* of the form $(w_P + \epsilon, \chi)$ and conditions B1-B3 to show that only those with $v_p \leq \chi - \frac{\chi E_H(B|s_H(v_p)) + cs_H(v_p) - \chi E_H(B|s_H(\chi)) - cs_H(\chi) - (\mu_H - \mu_L)r(1-\pi)}{(1-\pi)(E_H(B|s_H(v_p)) - E_L(B|s_L(v_p)))}$ survive *consistent high-failure deviations* of the form $(w_P + \epsilon, \chi)$. We then use Conditions A1-A3 to show that deviations of the form $(w_P + \epsilon, v_p + \delta)$ are *consistent low-failure deviations* that rule out all candidate pooling equilibria that satisfy $\chi \leq v_p < \chi + \frac{(\mu_H - \mu_L)r}{E_H(B|s_L(v_p)) - E_H(B|s_L(v_p))}$. Finally we show that together these three inequalities rule out all candidate pooling equilibria.□

Proof of Proposition 6: In a separating equilibrium (if it exists) the vendor is able to credibly signal his type. The best the H-type vendor can do is extract all the surplus of the buyer by setting $v_H^* = \chi$ and $w_H^* = -\mu_H r - \theta - \alpha_H M \mu_H$ for any α_H. His inventory is given by $s_H(x) = F_H^{-1}\left(1 - \frac{c}{x}\right) = \overline{s}_H$. The L-type's problem is then characterized by $\max_{w_L, v_L, \alpha_L} w_L - v_L E_L\left[B|s_L(v_L)\right] - cs_L(v_L) + \alpha_L M \mu_L$, subject to (IR_L): $-w_L + (v_L - \chi)E_L\left[B|s_L(v_L)\right] - \mu_L r - \alpha_L M \mu_L \geq \theta$, (IC_L): $w_L - v_L E_L\left[B|s_L(v_L)\right] - cs_L(v_L) + \alpha_L M \mu_L \geq -\mu_H r - \theta - \alpha_H M \mu_H - \chi E_L\left[B|s_L(\chi)\right] - cs_L(\chi) + \alpha_H M \mu_L$, and (IC_H): $-\mu_H r - \theta - \chi E_H\left[B|s_H(\chi)\right] - cs_H(v_H) \geq w_L - v_L E_H\left[B|s_H(v_L)\right] - cs_H(v_L) + \alpha_L M \mu_H$, where his inventory decision $s_L(v)$ given the performance based penalty $v \geq c$ is characterized by $s_L(v) = F_L^{-1}\left(1 - \frac{c}{v}\right)$. We conjecture that a contract with the following parameters constitutes a separating equilibrium that extracts first best rents $v_L = v_H = \chi$, $\alpha_L \leq -\frac{r}{M} \leq \alpha_H$; $\alpha_L < \alpha_H$, $w_L = -\alpha_L(M\mu_L + r) - \chi E_L\left[B|s_L(\chi)\right] - \theta$, $w_H^* = -\mu_H r - \theta - \alpha_H M \mu_H$. To show that this is the case, first observe that the inventory kept equal to first best, therefore first best outcomes are generated. Next, note that IR_L is binding, therefore the vendor extracts all rents. Finally the conditions placed on α_L and α_H ensure that both ICs are satisfied, without necessarily resulting in a pooling contract. The buyer's belief structure specified in the statement of the proposition ensures that neither type has any incentive to deviate unilaterally from this equilibrium.

To show that all candidate pooling equilibria (w_p, α_p, v_p) are eliminated we first use Conditions A1-A3, as specified under the description of the "intuitive criterion", to show that only those with $v_p \geq \chi + \frac{(\alpha_p M + r)(\mu_H - \mu_L)}{E_H(B|s_H(v_p)) - E_L(B|s_L(v_p))}$ survive *consistent low-failure deviations* of the form $(w_p + \epsilon, \alpha_p, v_p)$ and conditions B1-B3 to show that only those with $v_p \leq \chi + \frac{(\alpha_p M + r)(\mu_H - \mu_L)}{E_H(B|s_H(v_p)) - E_L(B|s_L(v_p))}$ survive *consistent high-failure deviations* of the form $(w_P + \epsilon, \alpha_p, v_p)$. From these two inequalities it is clear that we can restrict our attention to candidate pooling equilibria with $v_p = \chi + \frac{(\alpha_p M + r)(\mu_H - \mu_L)}{E_H(B|s_H(v_p)) - E_L(B|s_L(v_p))}$. We then use Conditions A1-A3 to show that deviations of the form $(w_P + \epsilon, \alpha, v)$ are *consistent low-failure deviations* that rule out all remaining candidate equilibria.□

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