Signaling and Contract Choice in After-Sales Service

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The extant literature on after-sales service support suggests an implicit consensus around the (Pareto) superiority of performance-based contracts (PBC) over traditional time-and-material contracts. However, when product technology is new, a setting in which the vendor possesses superior information on product reliability, there is compelling evidence to suggest that buyers prefer the traditional contracts. We undertake the first investigation into the role of after-sales contracts as a mechanism for signaling reliability. We find that while both PBC and the traditional contracts allow perfect signaling and coordinate the after-sales supply chain, only PBC allow the vendor to appropriate all rents. When the choice of contract class is endogenous, we show that this observation provides a formal explanation for the buyers' observed contractual preference. We also analyze the interaction of asymmetric information with moral hazard and find that PBC lead to overinvestment in inventory; we propose a contractual innovation that recovers efficiency.

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 civil aerospace sector, generating $43 billion in revenue in 2009 (Standard and Poor's 2011). For the customer organizations, namely airline companies, product reliability is a major concern: the products they acquire from the vendors – aircraft engines, for example – might occasionally fail. To avoid and overcome such failures, costly actions such as preventive, scheduled and unscheduled maintenance need to be undertaken. In this paper we restrict attention to failures that lead to instances of unscheduled maintenance as these are an unpredictable and significant form of expenditure.[1] As 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. The vendor offers an

[1] 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).

ex-post advantage over third-party service providers in being able to effectively resolve problems. However, could the vendor's superior knowledge create an *ex-ante* problem for the buyer? After all, how would the buyer, without access to the same information about product reliability, assess whether the (typically long-run) after-sales contract is fairly priced and sufficiently provisioned in terms of inventory of spares?[2] To investigate these questions, which are particularly salient when the product *technology* is relatively new and untested, we build a stylized model of after-sales services to investigate the operational and economic implications that this asymmetric information imposes on the contractual structures frequently observed in practice.

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 traditional transaction-based approach that encompasses the popular T&M contract (Adler et al. 2009). T&M relies 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 T&M contract, allowing the vendor to share the cost of repair and spare parts incurred after failure incidents.[3] PBC is a fundamentally different concept in which the vendor is compensated based on the realized performance outcome (e.g., aircraft up-time) instead of the amount of resources utilized for repairs.

PBC has gained traction in recent years because many customer organizations view it as a simpler approach to manage outsourced maintenance operations. There is a rich stream of literature that documents the advantages of PBC over RBC (e.g., Hypko et al. 2010, Kim et al. (2007,2010), Randall et al. 2011, Ward and Graves 2007). The main message from this literature is that by linking the vendor's compensation to realized performance, PBC is able to align incentives, i.e., induce optimal effort in reducing maintenance costs and optimal investment in inventory of spares.

Despite the prevailing consensus in the extant literature on the dominance of PBC over RBC, we continue to observe fervent support for both forms in practice.[4] The U.S. Government Accountability Office (GAO) reviewed the after-sales contracting practises of 14 private-sector companies,

[2] The 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). 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. An important feature of the product failures (unscheduled maintenance) is that they are relatively infrequent, e.g., for aircraft engines, the mean time between failures is of the order of 2 to 5 years (Guajardo et al. 2011). This substantially prolongs the duration over which the failure rate can be reliably learnt by the buyer through empirical observation of failures. Hence, information asymmetry is persistent.

[3] By incorporating cost-sharing (a warranty structure) into 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.

[4] There is an active debate currently underway amongst practitioners regarding the relative merits of the two contracting strategies (Guajardo et al. 2011, Ward and Graves 2007).

including 6 airline companies, and discovered that companies rely on RBC when the product technology is new (GAO 2004). The stated reason is that *the absence of accurate and reliable information on performance of new products results in an increased risk of negotiated prices being excessive with PBC*. While the GAO report documents the buyer's perspective, Ward and Graves (2007) surveyed vendors in the aerospace sector and found that the industry expects to continue to support both RBC and PBC into the future – the former being for *customers that prefer it*. These reported findings suggest that the advantages of PBC over RBC are not as obvious as suggested by the extant literature, especially when product technology is new, i.e., when there is asymmetric information regarding product performance between the vendor and the buyer. Our paper contributes to the literature by presenting a formal analysis of the operational and economic impact of this asymmetric information. We investigate a number of questions: Can the vendor credibly use the terms of the maintenance contract (RBC or PBC) to communicate her private information on reliability to the buyer?[5] How do the two strategies differ in their ability to achieve system efficiency and allocate rents in the supply chain? Does the presence of asymmetric information offer a consistent explanation for the observed preference amongst buyers for RBC? And, in equilibrium, is greater product availability (less backorders) always good news from an efficiency perspective?

To answer these questions we build a stylized model that captures the most important factors that influence the managerial decisions on after-sales maintenance contracting for new products. For concreteness, we frame our discussion with the civil aerospace sector in mind. In our model the vendor could possess a product with either high or low reliability, which is unknown to the buyer, and she offers specific contract terms to the buyer. Besides monetary transfers, the contract also specifies the inventory level of spare products that the vendor will maintain on behalf of the buyer.

Our main result shows that both PBC and RBC allow the vendor to credibly signal her quality to the buyer and achieve economic efficiency, i.e., efficient separating equilibria exist with either contract class. With PBC, the reliable vendor is able to signal her type by proposing a low level of inventory coupled with a relatively high fixed fee and high penalty-rate for downtime. The unreliable vendor finds it prohibitively costly to mimic at this inventory level and penalty-rate. In equilibrium, this leads to perfect separation. With RBC, the role of the performance-based penalty is taken by the proportion of cost retained by the vendor. The reliable type is able to signal by accepting to retain 100% of the maintenance costs incurred – something that the unreliable vendor again finds too expensive to mimic at the corresponding inventory and fixed fee specification. However, there is a critical and somewhat surprising difference – as opposed to PBC, RBC leads to the reliable type of vendor surrendering rents to the buyer. Using realistic parameters from

[5] Throughout the paper we refer to the vendor as she and the buyer as he.

the aerospace industry, we numerically estimate that the impact on the payoffs is in the order of millions of dollars per month depending on which contract class is selected.

Building further on these findings, we then augment our game-theoretic treatment to make the choice of contract class endogenous, and are thereby able to provide a formal explanation for the observed preference amongst buyers for RBC, when the product technology is new. This is because when the buyer exercises the right to choose a contract class, as is common practise in the civil aerospace sector, he chooses RBC and can thus steer the outcome of the game towards the RBC separating equilibrium that leaves him with surplus. The vendor can avoid this dilemma by *credibly* committing herself to offering only PBC, as some vendors such as Rolls-Royce seem to be doing.

We also perform a critical extension in which we relax the assumption that the inventory of spares is verifiable; an appropriate description when contracting parties have not invested in Information Systems that allow monitoring of the repair pipeline. In this setting, we argue that PBC is the only relevant contract class, and show that the PBC form analyzed in the literature and widely used in practice, that contracts only on availability (backorders), induces greater availability through overinvestment in inventory. This distortion arises due to a conflict between the dual role (signaling and incentive-alignment) played by the contract parameters. This result stands in contrast to the notion that in settings with moral hazard, a firm tends to underinvest in unverifiable effort. It is often argued that *when the equilibrium outcome is inefficient*, allowing for *ex-post* renegotiation (after signing a contract but before implementation) can eliminate inefficiency (Beaudry and Poitevin 1993, Inderst 2001). We show that accounting for renegotiation changes the equilibrium outcome: the payoffs are prior-dependent and the buyer's payoff can be lower than his *ex-ante* outside option. However, the overinvestment in inventory persists. Finally, we demonstrate that a more flexible yet operationally practical variant of PBC has the potential to alleviate this inefficiency by contracting on reliability (inconvenience cost) in addition to availability (backorders).

In summary, this paper is the first to analytically examine the performance of after-sales contracts in a setting with asymmetric information, and study their role as a mechanism for signaling reliability. By adopting a signaling perspective we are able to offer a formal explanation for some of the observed preferences over contractual arrangements. We also demonstrate that greater equilibrium availability can be inefficient. In the process, we provide the first (to our knowledge) application of signaling-cum-renegotiation games in the OM literature.

2. Literature Review

Our work relates to three distinct streams of literature. The first explicitly deals with PBC for outsourced services. The second stream, with which our work shares a methodological connection, is the literature on asymmetric information in operations management (OM). Finally, we discuss the connection with the literature on the use of warranties as a signaling mechanism.

PBC have been studied in service settings other than for aircraft engines by Roels et al. (2010), Gumus et al. (2011), and Jain et al. (2011).[6] PBC in the context of after-sales services for aircraft engines has been studied in Kim et al. (2007) and Kim et al. (2010). 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-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 product'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 products it sells and at the same time allows a reliable vendor to extract more rents from the buyer. Further, we identify circumstances under which asymmetric information implies that PBC will not be the favored mode of contracting. Another important distinction from the aforementioned work, which primarily focused on the defense sector, is that our model applies better to the civil aerospace sector where it is typically the *vendor* who takes the initiative in setting the contract parameters.

Our paper is related methodologically to the OM literature on games of asymmetric information. Examples of screening games, where the uninformed principal offers contracts designed to elicit information from the informed agent, include Corbett et al. (2004), Li and Debo (2009). Our work is closer to papers that adopt a signaling framework (e.g., Anand and Goyal 2009, Cachon and Lariviere 2001), where the informed principal signals their superior information through the contracts offered to the uninformed agent. To the best of our knowledge this paper is the first to focus on such signaling games in the after-sales service context, and also the first in OM literature to introduce renegotiations in a signaling framework.

The risk sharing and signaling capabilities of RBC and PBC result in characteristics similar to product warranties. Research on signaling product quality through 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. The underlying premise is that firms selling low-quality products will face higher costs for the same level of warranty than will high-quality

[6] 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).

firms, because low-quality firms' products are likely to require more frequent repair. A salient difference between our work and the quality-signaling 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. Unlike the B2C setting, B2B precludes strategies that allow signaling by trading-off differences in consumer characteristics, e.g., price sensitivity, attitude towards risk, intensity of product-usage, etc. Another point of departure from the extant literature is that in contrast to the common assumption that the costs of product failures are exogenous, we capture the possibility that the consequences of product failures can be mitigated through a managerial decision on spare inventory. More importantly, beyond identifying the scope for signaling, our primary interest is to contrast the performance of two specific and widely-used contracts in an after-sales context, i.e., RBC and PBC.

3. Model

We develop a stylized model that allows us to focus on our main objective, which is to characterize the impact of asymmetric information. We study a supply chain that consists of two risk-neutral parties, a vendor and a buyer; the latter faces a constant demand for product usage. To satisfy his 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. At the time of contract negotiation the vendor is perfectly informed about reliability of the product, while the buyer is not. After the contract terms are finalized, 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

During the course of deployment the products fail occasionally due to malfunction. The assumptions in this subsection, regarding the repair operations, are based on the standard spare parts inventory management models, as also elaborated in Kim et al. (2007, 2011). 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 $GI/G/\infty$ 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. We denote the expected number of product failures during the contracting period by μ. We assume that the arrival process for failures is exogenous and state independent. This is an approximation for two reasons. First, the repair process forms a closed loop cycle (i.e., repaired products are reintroduced into circulation) with finite population. This implies that the number of failures is a function of the number of working products over time. However, this approximation is not very restrictive: if the arrival process for failures is Poisson with rate μ, then the 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). Second, the arrival process may be influenced by preventive and scheduled maintenance which we do not explicitly model. Though crucial, preventive and scheduled maintenance are not significantly affected by contractual incentives. A bulk of the expenditure under these heads is either fixed or regulated. The discretionary component is not overly expensive to undertake, but shirking can lead to potentially disastrous consequences and loss of life.

A product typically is part of a revenue-generating system, e.g., engines in aircrafts. A product failure may affect system availability, which is defined as the fraction of system 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. As in Kim et al. (2007, 2011), we approximate all discrete variables (such as backorders and spare inventory level) as continuous variables, in order to facilitate game-theoretic analysis. Let F be the stationary distribution function of the inventory on-order O, i.e., the number of repairs being performed at the repair facility at a given point in time.[7] We assume that $F(x) = 0$ for $x < 0$ and the corresponding density function $f(x) > 0$ for $x > 0$; and the on-order distribution satisfies the increasing hazard rate property, i.e., $\frac{f(x)}{1-F(x)}$ is monotone increasing in x.[8] 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, performance can be measured in terms of expected backorders.

3.2. Description of Costs

Every time a product fails, it triggers a product-swap and the buyer incurs an inconvenience cost r. In the context of commercial airline operation, r represents, among other things, the cost associated with rescheduling flights that results from delays due to the engine coming off-wing for repair.[9] In addition, if the vendor does not have inventory on hand to replace the failed product the buyer incurs an additional cost χ per unit of system downtime. The cost χ represents the direct revenue

[7] When a one-for-one base stock policy is followed, O can be thought of as the number of busy servers in a $GI/G/\infty$ queue, the distribution for which is stationary for any finite repair lead time l (Kaplan 1975).

[8] The increasing hazard rate assumption is common in reliability theory and this property is satisfied by a wide range of distributions including Gamma, Weibull, Poisson and Truncated Normal (Barlow et al. 1963, Gupta et al. 1997).

[9] As explained in Adamides et al. (2004), "When a failure is detected ... the engine is grounded, taken off the aircraft and necessary repairs are accomplished...". Naturally this process leads to flight delays.

loss to the buyer from inoperability of the system due to the failed product, e.g., grounding of an aircraft. In expectation, this leads to a cost of $\mu r + \chi E[B|s]$.

For each failure, the vendor incurs an expected repair cost (inclusive of labor and component parts), 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.

A modeling assumption that we need to make is whether or not the inventory of spares is verifiable (and therefore contractible). On the one hand there exist commercial information systems that enable making 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 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)). On the other hand, not all firms have implemented such systems. Thus, verifiability of inventory can be thought of as an attribute of the vendor-buyer relationship.[10]

Accordingly we begin our analysis by treating inventory as being verifiable. As such, the vendor is able to specify the inventory level as part of contract terms (in RBC or PBC), and therefore, inventory level commitment can be used as an additional signaling device. We then relax this assumption and assume that the level of inventory is not observable, and therefore not contractible. This creates a moral hazard problem coupled with asymmetric information, leading to different dynamics: there is an interaction between the requirement to signal reliability and the need to provide adequate incentives for maintaining inventory.

In general, since PBC and RBC exhibit warranty-like features, another possible concern is that of 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. Specifically, the vendor charges an hourly engine rate that takes into account operating parameters beyond the amount of flight time, e.g., engine temperature and cycle utilization (p. 9 and 31 in Adler et al. (2009)). The main purpose of engine health monitoring (EHM) technology

[10] Another example that illustrates that verifiability is an attribute of the vendor-buyer relationship, is the Rolls-Royce TotalCare (PBC) program which provides spare engines on either dedicated or non-dedicated leases; the former is feasible only with verifiable inventory. See www.rolls-royce.com/civil/services/totalcare/, *Spare Engine Services* under *Optional Services* tab.

is to avoid disasters and costly repairs by enabling early detection of unexpected performance deterioration, and the generated data can even be audited by the regulator (e.g., Federal Aviation Administration) if required; elimination of user moral hazard is a collateral benefit to the vendor.

3.4. Negotiation Process and Contract Class

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. In our model the vendor leads the negotiations by initiating the contract offer, which is consistent with practice (Boito et al. 2009, p. 72). Besides, our focus is on complex products (with complex supply chains) for which the vendor possesses private information, which makes our assumption particularly appropriate. Further, the take-it-or-leave-it aspect of the contract offer is a reasonable abstraction for two reasons. First, this is consistent with the observation that the absence of competition on the supply side (technology is new and proprietary) results in a weaker bargaining position for the buyer during contract negotiation (GAO 2006). Second, we note that in sectors such as civil aerospace, the vendors are powerful organizations (with huge asset-base and market capitalization) such as GE and Rolls-Royce that enjoy tremendous bargaining power, while the buying firms are airline companies that can be of various sizes. Note that some prior work in the after-sales literature (e.g., Kim et al. (2007) and Kim et al. (2010)) model the buyer as the principal to reflect the importance of the defense sector in negotiations, in combination with the implicit existence of competitive alternatives on the supply side when technology is mature.

Another important determinant of bargaining power is the ability to choose the contract class (whether RBC or PBC). We discuss this issue and its implications in §5.3. Until then we assume that the contract class is exogenously specified.

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. 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. With either contract, the fixed fee can be interpreted to be inclusive of product price.

A contract, $\mathbf{C}$, is a vector of real-valued parameters. It involves an expected transfer payment, $T(\mathbf{C})$, from the buyer to the vendor in return for maintenance support. The maximum possible revenues the buyer would generate, assuming there is no disruption, is denoted by the constant R. The buyer's expected 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 expected payoff is $V(\mathbf{C}) = T(\mathbf{C}) - cs - \mu M$.

The contract parameters under RBC can be represented as $\mathbf{C} = (w, \alpha, s)$ or (w, α), depending on whether or not inventory s is verifiable, where w represents the fixed fee and $\alpha \geq 0$ represents the buyer's share of the cost of repair and maintenance for each failure. The transfer payment can be represented as $T(\mathbf{C}) = w + \alpha\mu M$. We do not allow α to take on negative values in an RBC, since that would make the contract performance-based, which we study separately albeit in a different parametric form. 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. Specifically, under PBC, the contract parameters can be represented as $\mathbf{C} = (w, v, s)$ or (w, v), where the performance component v is used to impose a penalty if the failure results in downtime due to insufficient spares (backorders). The transfer payment can be represented as $T(\mathbf{C}) = w - vE[B|s]$.[11]

4. Complete Information and 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: $U = -w - \chi E(B|s) - \mu r \geqslant \theta$. An overbar on a symbol denotes the corresponding first-best outcome. We now 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, or are included in the main text. Since there are no distortions or informational asymmetries it is not surprising that a contract based on fixed fee and inventory only 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.

Now consider the possibility that the vendor could be either of two types: L or H. Under complete information both parties observe the type of the vendor perfectly. Type L denotes the unreliable type of vendor while type H denotes the reliable vendor. The corresponding number of expected failures in the contract duration is such that $\mu_L > \mu_H$ and the on-order inventory O_L and O_H follow the distributions F_L and F_H, respectively. Further, we assume that there is a strict hazard

[11] For convenience, we suppress the notation for the vector, $\mathbf{C}$, whenever it does not cause confusion.

rate ordering between O_L and O_H, i.e., $\frac{f_L(x)}{1-F_L(x)} > \frac{f_H(x)}{1-F_H(x)}, \forall x > 0$. This is not overly restrictive assumption; for example, if the arrival process for failures Poisson with rate μ, then by Palm's Theorem we know that the stationary on-order distribution is also Poisson with rate μl (Feeney and Sherbrooke 1966), which exhibits hazard rate ordering.[12]

Further to generating fewer expected failures, does the reliable vendor perform better than the unreliable vendor on the availability performance metric, i.e., does contracting with the reliable vendor result in lower expected backorders: $E[B|s] = \int_s^\infty (1 - F(x))dx)$? As it turns out the hazard rate ordering is not sufficient to ensure that this is the case. Instead, a sufficient condition is:

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

This condition is the definition of the excess wealth (EW) order, also known as "right spread" order (see definition 3.C.1 in Shaked and Shanthikumar (2007)). If the failure processes are Poisson, then they satisfy the EW order, which is sufficient for condition (1) to hold (using Theorem 3.C.4 in Shaked and Shanthikumar (2007)).[13]

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.,* $\overline{V}_H > \overline{V}_L$*; and the reliable vendor chooses a lower inventory level than the unreliable vendor, i.e.,* $\overline{s}_H < \overline{s}_L$*.*

The above result confirms our intuition that the reliable type of vendor is better-off than the unreliable type when there is complete information. Furthermore, the reliable type's lower inventory and higher payoff imply that the first-best contracts will not be incentive compatible – the unreliable type will have 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.

5. The Signaling Game

As discussed in the Introduction, when the product technology is new the vendor has superior information about the failure distribution of the products that it sells to the buyer. In particular, we assume that the vendor observes her type perfectly, while the buyer believes ex-ante that the vendor is of type L with probability $\pi > 0$. Further, we assume that this belief is *common knowledge.*

[12] It is straightforward to verify that Poisson distributions exhibit the (discrete) likelihood ratio ordering, i.e., $\frac{(\mu_L)^k e^{-\mu_L}/k!}{(\mu_H)^k e^{-\mu_H}/k!}$ is monotone increasing in k; which then implies the (discrete) hazard rate ordering.

[13] In general, by Theorem 3.C.8 in Shaked and Shanthikumar (2007), a random variable X is smaller in EW order than $X + Y$, for any random variable Y independent of X if, and only if, X exhibits increasing hazard rate.

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 his beliefs about vendor's type, and accepts or rejects the contract.
4. Vendor decides the inventory level of spares to be maintained (if not specified in the contract); products are deployed, failures occur, and repair and maintenance takes place; transfer payment is made by buyer and final payoffs are realized by both players.

Essentially, 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. The equilibrium concept that we work with is perfect Bayesian equilibrium (PBE) along with refinements – namely the "intuitive criterion" proposed by Cho and Kreps (1987). (See Appendix A for more details.) We now investigate this setting first with RBC and then with PBC arrangements. Thereafter, we adapt the above sequence of events in order to explore issues around choice of contract class (i.e., RBC or PBC?). We restrict our attention to characterizing separating equilibria, since pooling equilibria are eliminated by refinements and plausibility arguments (see Appendix A).

5.1. Equilibrium Characterization with Resource-Based Contracts

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. 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: $U_\tau = -T_\tau - \chi E_\tau(B|s_\tau) - \mu_\tau r = -w_\tau - \alpha_\tau \mu_\tau M - \chi E_\tau(B|s_\tau) - \mu_\tau r$.

All separating equilibria must satisfy the following participation (IR_τ) and incentive compatibility (IC_τ) constraints, where $\tau' \in \{L, H\} \backslash \tau$:

$$-w_\tau - \alpha_\tau \mu_\tau M - \chi E_\tau(B|s_\tau) - \mu_\tau r \geq \theta, \tag{IR_τ}$$

$$w_\tau - (1 - \alpha_\tau)\mu_\tau M - cs_\tau \geq w_{\tau'} - (1 - \alpha_{\tau'})\mu_\tau M - cs_{\tau'}. \tag{IC_τ}$$

The constraints (IR_H) and (IR_L) ensure that the buyer dealing with the reliable and unreliable vendor respectively, makes at least his reservation value and therefore would willingly participate. The constraints (IC_H) and (IC_L) 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 that 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. Does RBC allow the reliable vendor to credibly signal her type by agreeing to set a lower α than the unreliable type? We summarize our results with the following proposition.

PROPOSITION 2. *With RBC, 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., $V_L^* = \overline{V}_L$.

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

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

$$0 = \alpha_H^* \le \alpha_L^*,\ s_L^* = \overline{s}_L,\ w_L^* = -\theta - \mu_L r - \chi E_L(B|\overline{s}_L) - \alpha_L^* \mu_L M,$$

$$\max\{0, s^m\} \le s_H^*, \overline{s}_H \le s^M,\ w_H^* = -\theta - \mu_L r - \chi E_L(B|\overline{s}_L) + c(s_H^* - \overline{s}_L),$$

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

d) There exist economically efficient and Pareto optimal separating equilibria with $s_H^* = \overline{s}_H$.

The preceding proposition shows that it is possible to signal under RBC. In any separating equilibrium the reliable vendor will offer full warranty ($\alpha_H = 0$), but this is not necessarily the case for the unreliable vendor. Further, there exist multiple separating equilibria (with $s_H^* \in [\max\{0, s^m\}, s^M]$) and in every one of these equilibria the reliable vendor surrenders rent to the buyer in order to signal her type. 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 since $s_H^* = \overline{s}_H$ is a feasible outcome in equilibrium. These particular equilibria (with $s_H^* = \overline{s}_H$) allocate the maximum possible rent to the buyer (out of the class of all equilibria identified in Proposition 2). Furthermore they are economically (and Pareto) efficient.[14] We adhere to the standard argument in economics that one of the Pareto optimal equilibria will be the outcome in a game with multiple equilibria (for instance, see Spence (2002)).

So why is the reliable vendor unable to recover first-best rents in any separating equilibrium? The reason is as follows. The reliable vendor simultaneously optimizes her profits and deters mimicking

[14] 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 ($\overline{s}_L$ and $\overline{s}_H$ for the L and H-type respectively). Since $\max\{0, s^m\} \le \overline{s}_H \le s^M$, therefore, there do exist separating equilibria with $s_H^* = \overline{s}_H$. Note that a continuum of such economically efficient equilibria are possible, each with a different value for $\alpha_L^* \ge 0$, but resulting in exactly the same payoffs for all player-types.

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 vendor could have potentially differentiated herself by offering a greater warranty (lower α) while maintaining first-best inventory ($\overline{s}_H$). Further, in order to achieve 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 vendor to mimic, i.e., hold the inventory of the H-type and offer the H-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., $\alpha_H^* = 0$. 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. Since the first-best contracts are not incentive compatible, the reliable vendor has to settle for a lower payoff such that it is not profitable for the unreliable vendor to mimic. Any choice of inventory level, s_H^*, in the interval $[\max\{0, s^m\}, s^M]$, leaves the vendor indifferent since she can trade-off inventory costs against the fixed fee to achieve the exact same payoff without affecting the incentive compatibility constraints, but the specific choice $\overline{s}_H$ leaves maximal rents with the buyer and is Pareto optimal.

Having analyzed the equilibrium outcomes with RBC, we now turn our attention to PBC.

5.2. Equilibrium Characterization with Performance-Based Contracts

In this case 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. This reflects the situation where the vendor is penalized for downtime which is proportional to the number of backorders. 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 revisit the characterization of the participation (IR) and incentive compatibility (IC) constraints. All equilibria must satisfy the following constraints, where $\tau' \in \{L, H\}\backslash\tau$:

$$-w_\tau + (v_\tau - \chi)E_\tau(B|s_H) - \mu_\tau r \geq \theta, \tag{IR$_\tau$}$$

$$w_\tau - v_\tau E_\tau(B|s_H) - cs_\tau - \mu_\tau M \geq w_{\tau'} - v_{\tau'} E_\tau(B|s_{\tau'}) - cs_{\tau'} - \mu_\tau M. \tag{IC$_\tau$}$$

We summarize our results below.

PROPOSITION 3. *With PBC, there exist multiple separating equilibria that allow the vendor to signal her type. Each of these PBE exhibits the following properties:*

a) Each type of vendor achieves her first-best payoff, i.e., $V_L^* = \overline{V}_L$ *and* $V_H^* = \overline{V}_H$*.*

b) These PBE are characterized by the strategies (w_H^*, v_H^*, s_H^*) *and* (w_L^*, v_L^*, s_L^*) *for the L-type and H-type vendor respectively, such that* (IR_H) *and* (IR_L) *are binding, and the following relationships hold for* $\tau \in \{L, H\}$*:*

$$w_\tau^* = -\theta - \mu_\tau r + (v_\tau^* - \chi) E_\tau(B|\overline{s}_\tau); s_\tau^* = \overline{s}_\tau, \tag{2}$$

$$v_L^* \left[E_L(B|\overline{s}_L) - E_H(B|\overline{s}_L) \right] \leq \chi [E_L(B|\overline{s}_L) - E_H(B|\overline{s}_H)] + (\mu_L - \mu_H) r + c(\overline{s}_L - \overline{s}_H) \leq v_H^* \left[E_L(B|\overline{s}_H) - E_H(B|\overline{s}_H) \right]. \tag{3}$$

Given that first-best payoffs are achieved, we have established that, with PBC, the presence of asymmetric information has effectively no impact on the payoffs of the contracting parties. The vendor is able to credibly and efficiently signal her type with PBC because of 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.

Even though the occurrence of a fully efficient separating equilibrium that results in first-best outcomes is relatively rare in the signaling literature, it does constitute the first of three categories of qualitatively different equilibria that may arise in typical signaling games (Spence 2002). The other two being the standard (inefficient) separating equilibria and the pooling equilibria respectively. As Spence (2002) points out, in essence, the two types are sufficiently different in terms of some combination of (w, v, s) such that the first-best outcomes are incentive compatible. However, the negative relation between the penalty rate v and the payoff of the vendor really matters. If the signaling costs had been the same for the two types, then we could not have achieved separation.

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 (not RBC) 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.

Thus, having characterized the equilibrium outcomes with RBC and PBC, we are now ready to enhance our treatment in order to make the choice of contract class endogenous.

5.3. Endogenous Choice of Contract Class

In §5.1 and §5.2 we assumed that the contract class (RBC or PBC) is exogenously specified. In this section we relax this assumption in order to determine which contract class will be chosen in equilibrium. Instead we assume that the player choosing the contract class (buyer or vendor), is exogenously specified. Given the negotiation process of our setting, in which the privately informed vendor of a complex product with a complex supply chain offers the contract terms, it is natural to analyze the case in which the choice of contract class is made by the vendor. Nevertheless, in the civil aerospace sector it appears to often be the case that the vendor offers the customer the choice of contract class. For instance, the online promotional material for OnPoint Solutions – GE Aviation's version of PBC – states that, "For *customers who prefer* a more customized, comprehensive and longer-term solution ... GE brings ... our OnPoint Solutions offering." Similarly, Pratt & Whitney offers its customers a choice between its Fleet Management Program (PBC) and traditional contracts (p. 27 in Adler et al. (2009)). Therefore we analyze both the case where the vendor or the buyer gets to choose the contract class.

A formal treatment is in order since such a choice alters the sequence of events in the game and, in principle, the choice of contract class itself could reveal information and thereby alter the rent allocations. We augment our game-structure to reflect the following sequence of events:

1. Nature reveals to the vendor her reliability (type), $\tau \in \{L, H\}$.

2. Player i announces its choice of the contract class only (either RBC or PBC) and not the specific contract terms. Player i's identity (whether vendor or buyer) is exogenously specified.

3. If the vendor chooses the contract class in the previous step, then based on this choice, the buyer updates his beliefs about the vendor's reliability (type).

4. Vendor offers specific contract terms (possibly type-contingent) to buyer. The contract class was determined by announcement in step 2.

5. Based on the proposed contract terms, buyer further updates his beliefs about vendor's reliability (type), and accepts or rejects the contract.

6. Products are deployed, failures occur, and repair and maintenance takes place; transfer payment is made by buyer and final payoffs are realized by both players.

Since we have already done most of the work to analyze the augmented game in §§5.1 and 5.2, we are able to state and prove a key result in our paper:

Proposition 4. *In the game with endogenous choice of contract class:*

a) If the vendor chooses the contract class, then all player-types will achieve their first-best payoffs in equilibrium and the vendor captures the entire surplus. The reliable type of vendor will choose PBC, while the unreliable type is indifferent in her choice between PBC and RBC.

b) If the buyer chooses the contract class, then RBC will be selected and the payoffs will be determined as per the separating equilibrium in Proposition 2, i.e., the buyer captures all the surplus.

Proof: For part a) there are two possible equilibria that might be played out. The first possibility is a partially separating equilibrium in which both types of the vendor pool in step 2 and choose PBC, and thereafter the separating equilibrium in Proposition 3 is played out; the buyer maintains his prior belief in step 3, but updates his beliefs in step 5 after observing the contract offer. Alternately, a fully separating equilibrium would lead to the reliable vendor choosing PBC and the unreliable vendor choosing RBC in step 2; the buyer updates his beliefs to reflect the perfect separation of types; thereafter the first-best contracts under complete information are agreed upon. Significantly, both of these equilibria are payoff-equivalent.[15]

In part b) the buyer will choose RBC and thereafter the RBC separating equilibrium (Proposition 2) is played out. The buyer cannot do better in any other outcome. Note that the buyer's choice is step 2 reveals no information since he is the uninformed party. □

The above proposition has two interesting interesting implications. First, it provides a formal explanation for the observation that buyer organizations (not limited to the aerospace sector) choose the traditional time-and-material contract in preference to PBC, when the product technology is new and the buyer does not have perfect information on product reliability (GAO 2004). By exercising their prerogative to choose the contract class, buyers will opt for RBC as the corresponding equilibrium outcome leaves them with rent. Second, it offers insight into why some vendors appear to be committing themselves to solely offering PBC. This commitment has to be credible for it to work and one way of achieving this is through extensive marketing and media campaigns (Ward and Graves 2007). The benefits to the vendor from such a strategy are clear enough – she can restrict the outcome of the game to PBC separating equilibrium, as the issue of contract choice becomes moot. Rolls-Royce (RR) and International Aero Engines (IAE) are possibly adherents to this strategy. Since 2001, 80% of RR's Trent engine orders have incorporated PBC; while around 90% of IAE's new deals are under PBC. Adopting such a stance is by no means straightforward and costless, owing to buyer resistance which we can now understand better based on the results in Proposition 4. Such cost barriers are organization-specific and could lead to different strategic perspectives. For instance, only about 30% of Pratt & Whitney's engine overhauls are covered by PBC. Going forward, they actually expect a slowdown in their use of PBC (Adler et al. 2009). The above discussion is consistent with the observation in Ward and Graves (2007) that in the future, besides PBC, vendors expect to continue supporting RBC for *customers that prefer it.*

Up to this point in our analysis we have assumed that inventory of spares is contractible. However, this may not be an adequate description when contracting parties do not/cannot invest in systems that make an audit feasible. This does raise an important question: How would the interaction of asymmetric information with the need for incentive alignment affect the equilibrium outcome? We address this issue in the next section.

[15] An alternate means to analyze contract choice by the vendor would be to model the contract parameters as (w, α, v, s) with $\alpha \geq 0$. This would preclude the need to augment the sequence of events by including step 2. Qualitatively speaking, we would recover the same equilibrium outcomes as in Proposition 4; since the separating equilibrium in Proposition 3 would still be an equilibrium for this game (and it is unique with respect to payoffs). Also, note that a special case of this equilibrium involves $v_L^* = 0$, which could be thought of as RBC.

6. Signaling with Unverifiable Inventory

We extend our analysis to the case in which the spares inventory maintained by the vendor is not observable or verifiable by the buyer. Even though it is theoretically feasible to have RBC 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., $s_H^* = s_L^* = 0$. This would result in substantial inefficiencies. Our analysis would therefore predict that when asymmetric information is coupled with unverifiable inventory then RBC would not be a popular mode of contracting. (Further, we note that this contract type is a special case of the contract form discussed in §6.2.) Hence, we restrict our treatment in this section to the analysis of PBC.

Recall that when inventory is verifiable, the vendor is able to use the performance-based component, v_τ, of the contract to credibly signal the quality of her engines and 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 sufficient 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 hazard rate ordering between O_L and O_H we will also make the assumption that they satisfy the EW order. This condition is sufficient to uniquely characterize the payoffs in the second best contract.

Proposition 5. *With PBC and unverifiable inventory:*

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

b) If O_L and O_H satisfy the EW order, then separating equilibria always exist; (IR_H), (IR_L) and (IC_L) are binding such that: $v_L^* = \chi$; $w_L^* = -\theta - \mu_L r$; $w_H^* = -\theta - \mu_H r + (v_H^* - \chi)E_H[B|s_H(v_H^*)]$; and v_H^* is the unique solution of:

$$\chi E_L(B|\bar{s}_L) - v_H E_L(B|s_L(v_H)) + (v_H - \chi)E_H(B|s_H(v_H)) + c\,(\bar{s}_L - s_L(v_H)) + (\mu_L - \mu_H)r = 0. \quad (4)$$

Further, $v_H^* \in (\chi, \infty)$. The inventory decisions $s_\tau(v)$, where $\tau \in \{L, H\}$ and v is the performance based penalty, are characterized by $s_\tau(v) = F_\tau^{-1}\left(1 - \frac{c}{v}\right)$.

The above proposition describes a second-best contract in which the outcome is qualitatively similar to that in job-market signaling (Spence 1973), i.e., the efficient type destroys economic value in order to signal her type. Since $v_H^* > \chi$, we can conclude that $s_H^* > \bar{s}_H$, or that the reliable vendor overinvests in inventory. This happens because the reliable vendor is willing to take a high enough penalty on backorders (which the unreliable vendor finds prohibitively high to bear even if it comes with the higher fixed fee w_H), in order to signal and differentiate herself from the unreliable vendor. However, in order to counterbalance this additional exposure, the reliable vendor decides to maintain a higher inventory level of spares so that the expected backorders go down. Since spares are costly this results in loss of value. Note that this result is qualitatively different to the result of RBC under verifiable inventory (§5.1) where in order to send a credible signal the reliable vendor did not need to destroy economic value but instead surrendered rents to the buyer. Generally, our intuition about settings with moral hazard suggests that a firm would shirk by underinvesting in effort. However, by jointly accounting for the need to signal private information and disutility from effort, we find that in equilibrium the vendor overinvests in effort.

It may be argued that contracts in which the choice of effort (inventory) is not efficient will not survive possible renegotiations after the contract has been signed but before it has been implemented.[16] If the parties cannot commit not to renegotiate, then after the contract in Proposition 5 has been signed, the reliable vendor could offer the buyer a Pareto improving proposal, which will certainly be accepted by the buyer, thereby destroying the initial equilibrium. The unreliable vendor would anticipate this and be more aggressive in trying to mimic the reliable vendor. This issue is our focus in the next section.

6.1. Signaling and Renegotiation

In this section we explicitly account for the possibility of renegotiations. The framework laid out in Beaudry and Poitevin (1993), suitably extended to account for moral hazard as well as asymmetric information, is remarkably appropriate for our context. Essentially we capture the idea that after signing a contract but before execution, the vendor has the ability to offer a renegotiated proposal to the buyer, which will be accepted provided the buyer's payoff is no less than before, irrespective of what he believes about the vendor's type. To counter end-horizon effects, we allow for a (potentially) infinite rounds of renegotiation in which the vendor can make proposals and the buyer can accept or reject them. For this analysis to go through it is essential that explicit contracts are used in each round, as is the case in our setting. If the initial proposal from the vendor is refused then the game ends. In subsequent rounds, in case a (renegotiated) proposal is refused by the buyer then the players default to the previously agreed upon explicit contract. We denote the least-cost separating equilibrium found in Proposition 5 by the notation $\mathbf{C}_\tau^s = \{w_\tau^s, v_\tau^s\}$, for $\tau \in \{L, H\}$. As per this framework for signaling-cum-renegotiation, any pair of contracts $\mathbf{C}_\tau = \{w_\tau, v_\tau\}$, for $\tau \in \{L, H\}$, can be supported as an outcome of a PBE *if and only if* the contracts satisfy the following conditions:

i) $\pi U_L(\mathbf{C}_L) + (1-\pi) U_H(\mathbf{C}_H) \geq \theta$,

ii) $V_L(\mathbf{C}_L) \geq [\max_C V_L(C) \text{ subject to } U_L(C) \geq \theta]$,

iii) $V_H(\mathbf{C}_H) \geq [\max_C V_H(C) \text{ subject to } U_L(C) \geq \theta]$,

[16] Since all equilibria discussed in §5 are efficient, the issue of renegotiations is not relevant when inventory is verifiable.

iv) $V_H(\mathbf{C}_H) \geq [\max_C V_H(C)$ subject to $U_H(C) \geq U_H(\mathbf{C}_L)$; and $U_L(C) \geq U_L(\mathbf{C}_L)]$,

v) $V_L(\mathbf{C}_L) \geq [\max_C V_L(C)$ subject to $U_H(C) \geq U_H(\mathbf{C}_H)$; and $U_L(C) \geq U_L(\mathbf{C}_H)]$,

vi) $V_H(\mathbf{C}_H) \geq [\max_C V_H(C)$ subject to $U_H(C) \geq U_H(\mathbf{C}_H)$; and $U_L(C) \geq U_L(\mathbf{C}_H)]$,

vii) $V_L(\mathbf{C}_L) \geq [\max_C V_L(C)$ subject to $U_H(C) \geq U_H(\mathbf{C}_L)$; and $U_L(C) \geq U_L(\mathbf{C}_L)]$,

viii) if $\mathbf{C}_L \neq \mathbf{C}_L^s$ and $\mathbf{C}_L \neq \mathbf{C}_H$, then for $\tau \in \{L, H\}$:

$V_\tau(\mathbf{C}_\tau) \geq [\max_C V_\tau(C)$ subject to $U_H(C) \geq U_H(\mathbf{C}_H)$; and $U_L(C) \geq U_L(\mathbf{C}_L)]$.

Condition (i) is the buyer's *ex-ante* participation constraint, while conditions (ii) and (iii) ensure that in equilibrium the vendor can do no worse than the extreme situation when the buyer believes that she is the unreliable type for sure. The other conditions capture the effect of the renegotiation process. An essential aspect of the conditions (iv) - (vii) is that a buyer will accept a renegotiation if, regardless of his beliefs, he cannot lose by accepting the renegotiation. Specifically, conditions (vi) and (vii) indicate that starting from her equilibrium contract, the vendor cannot propose a Pareto improving renegotiation. Conditions (iv) and (v) convey the same intuition, except that the starting point is the other type's equilibrium contract. Beaudry and Poitevin (1993) refer to the latter as the *renegotiation-induced incentive-compatibility constraints*. Condition (viii) is an attainability condition on all separating outcomes such that $\mathbf{C}_L \neq \mathbf{C}_L^s$.

Due to the dynamic nature of the renegotiation process the set of possible PBE is generally much larger than in the one-shot signalling games which we investigated in the previous Section. Nevertheless, the least-cost separating equilibrium of the one-shot game outlined in Proposition 5 does not belong to this set – it never survives the renegotiation process (see Corollary 1 Beaudry and Poitevin (1993)). In order to winnow down the PBE of the signaling-cum-renegotiation game we use a stronger equilibrium refinement, namely the *Extended-Divinity (XD) Criterion.*[17] For brevity, we introduce some new notation: $F_p(.) = \pi F_L(.) + (1-\pi)F_H(.)$, $\mu_p = \pi\mu_L + (1-\pi)\mu_H$, and $E_p(B|s(v)) = \pi E_L(B|s_L(v)) + (1-\pi)E_H(B|s_H(v))$. We summarize the *payoff-unique* PBE outcomes of the signaling-cum-renegotiation game that satisfy the XD criterion below.

Proposition 6. *If O_L and O_H satisfy the EW order, then any equilibrium outcome of the signaling-cum-renegotiation game exhibits the following features:*

a) It is unique with respect to payoff and is inefficient.

b) The contract parameters are: $w_H^* = (v_H^* - \chi)E_p(B|s(v_H^*)) - \mu_p r - \theta$; and $v_H^* > \chi$ such that it solves the equation below (in case of multiple solutions, v_H^* maximizes the reliable vendor's payoff):

$$\frac{(v-\chi)c}{v^2}\left((1-\pi)\frac{1-F_H(s_H(v))}{f_H(s_H(v))} + \pi\frac{1-F_L(s_L(v))}{f_L(s_L(v))}\right) = \pi\left(E_L(B|s_L(v)) - E_H(B|s_H(v))\right), \qquad (5)$$

$v_L^* = \chi$; $w_L^* = (1-\pi)(v_H^* - \chi)\left(E_H(B|s_H(v_H^*)) - E_L(B|s_L(v_H^*))\right) - \mu_p r - \theta$. The inventory decisions $s_\tau(v)$, where $\tau \in \{L, H\}$ and v is the performance-based penalty, are characterized by $s_\tau(v) = F_\tau^{-1}\left(1 - \frac{c}{v}\right)$.

[17] This refinement subsumes the "intuitive criterion". For more details, please refer to Beaudry and Poitevin (1993).

As in Proposition 5, the renegotiation proof equilibria are inefficient since the reliable vendor overinvests in inventory (since $v_H^* > \chi \Rightarrow s_H^* > \overline{s}_H$), yet the two sets of equilibria are qualitatively different in two significant ways. First, the payoffs now depend on the prior probability, π, a feature that is entirely absent in any separating equilibrium in a one-shot signaling game. Second, even in a separating equilibrium, the buyer now earns lower than his *ex-ante* outside option (before he learns the vendor's type) when dealing with either the unreliable or reliable vendor, since $\pi U_L(\mathbf{C}_L) + (1-\pi)U_H(\mathbf{C}_H) = \theta$ (see proof of proposition in Appendix B). To understand why this happens consider one equilibrium path supporting the equilibrium outcome: along the equilibrium path, each type of vendor offers $\mathbf{C}_H$ in the first stage of the renegotiation game, i.e., the vendor pools. In the subsequent stage, the reliable vendor does not change her offer but the unreliable type offers $\mathbf{C}_L$ such that $U_L(\mathbf{C}_L) = U_L(\mathbf{C}_H)$. These offers will not be further renegotiated. Since, in the first round the buyer had accepted the pooled contract, he will accept the contracts of either type in the subsequent round because he can be no worse-off than his default outcome (the pooled contract from the first stage), even though he may be worse-off than his *ex-ante* outside option.

Our motivation behind studying renegotiations was the inefficiency of the one-shot separating equilibrium – the reliable vendor overinvests in inventory. While renegotiation might alleviate this inefficiency and lead to an improvement in supply-chain efficiency, accounting for renegotiation might make the unreliable vendor more aggressive in her attempt to mimic. In §7 we show numerically that both predictions are borne out.

6.2. Performance in terms of Backorders and Inconvenience Cost

When inventory is unverifiable, PBC cannot fully restore efficiency even if multiple rounds of renegotiation are allowed to take place. 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 this section by allowing contracting on reliability, or every instance of unscheduled maintenance, in addition to backorders.

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). 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: $U_\tau = -T_\tau - \chi E_\tau(B|s_\tau) - \mu_\tau r = -w_\tau - \alpha_\tau \mu_\tau M + (v_\tau - \chi)E_\tau(B|s_\tau) - \mu_\tau r$. The equilibrium outcome can be characterized as follows:

Proposition 7. *With PBC on backorders and inconvenience cost, and unverifiable inventory, there exist separating equilibria. Moreover, in each of these PBE, (IR_L) and (IR_H) are binding such that both types of the vendor achieve first-best, and therefore economic efficiency:* $v_H^* = v_L^* = \chi$, $\alpha_H^* \le -\frac{r}{M} \le \alpha_L^*$; $\alpha_H^* < \alpha_L^*$, $w_H^* = -(\alpha_H^* M + r)\mu_H - \theta$; $w_L^* = -(\alpha_L^* M + r)\mu_L - \theta$, $s_H^* = \bar{s}_H$; $s_L^* = \bar{s}_L$.

These contracts retrieve first-best outcomes because they delineate the signaling from the moral hazard problem. By setting $v_L^* = v_H^* = \chi$, the contract induces efficient inventory investment, and the residual problem is one of pure signaling where α can be negative. As we argue §5.2, penalizing the vendor for inconvenience was mathematically equivalent to choosing a negative α_τ, and that when inventory is verifiable a PBC incorporating negative α suffices to signal efficiently. Consequently, even when inventory is unverifiable, we are able to recover efficient separating equilibria that are qualitatively similar to those in Proposition 3.

In contrast to the form of PBC currently used in practice, we have shown that a more flexible form that contracts on both availability (backorders) and reliability (inconvenience cost) could potentially lead to economic efficiency even with unverifiable inventory. This might appear counter-intuitive from the vendor's perspective, since offering 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.

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

7. Illustrative Numerical Examples

The analysis presented in §§5 and 6 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 civil aerospace sector, summarized in Table 1, to demonstrate that this is indeed the case. The failure distributions are Poisson, as it satisfies all assumptions made in the paper.[18] The chosen unit of analysis is one month as payments between airlines and vendors are typically exchanged monthly. In these examples the buyer's outside option is normalized to 0. Payoffs reported are negative as we focus only on the cost side. As shown in figure 1, when $\mu_L/\mu_H = 5/3$ (right extreme on the x-axis) the gap between the first-best revenues for the vendor types is about \$2 million

[18] Since the game-theoretic treatment in the paper relies on a continuous approximation of discrete variables, we use the Normal approximation for the Poisson distribution – as justified in detail in Kim et al. (2007).

	Definition	Value	Source
χ	Backorder cost	\$2,000,000 per month	Estimated based on revenue per aircraft figures reported by airlinefinancials.com, an independent airline industry consulting firm.
c	Cost per spare	\$70,000 per month	Estimated based on engine lease-rental rates (Canaday 2010) and cost of a spare engine (Adler et al. 2009).
$1/\mu_H$	Expected time between failures for H-type vendor	3-5 years	Within range reported in Guajardo et al. (2011).
$1/\mu_L$	Expected time between failures for L-type vendor	3 years	Within range reported in Guajardo et al. (2011).
r	Inconvenience cost	\$175,000	Engine replacement time $\sim$ 2 days; linear extrapolation at rate of \$61 per minute of delay (Ramdas et al. 2012).
N	Number of engines	150	Order size for large airline (Kim et al. 2007).
M	Cost per unscheduled maintenance	\$800,000	Estimated based on industry expert inputs and consistent with figures reported in Hopper (1998).
l	average repair lead time for engine overhaul	3 months	Based on numbers in Adamides et al. (2004) (accounting for operational improvements).

Table 1 Parameter Values

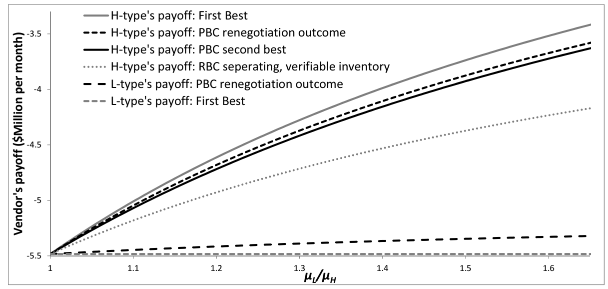

Figure 1 Vendor's Payoffs $(\pi = 0.5)$

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.[19] We also note that the PBC contract based on backorders (Proposition 5), which is used in practice, destroys value of a few hundred thousand dollars a month for the H-type vendor. This value can be recovered by using the PBC on availability and reliability (Proposition 7). It is worth noting that the RBC separating equilibrium (Proposition 2) can leave significant rents with the buyer. These can be as much as the difference between the H-type's payoff in the RBC separating equilibrium and her first-best rents (which is approximately \$800,000 per month when $\mu_L/\mu_H = 5/3$).

We can also use the results in figures 1-5 to strengthen our understanding of the renegotiation outcome when inventory is unverifiable. The driver of efficiency in our analysis is inventory and from figure 2 we observe that renegotiation results in substantial improvement in efficiency (inventory costs are close to first-best). Who captures this efficiency gain? Recall we had argued in §6 that the unreliable vendor would be more aggressive in her mimicking behavior since she anticipates the efficiency gains from renegotiation. From figure 1 we see that this intuition is borne out as the unreliable vendor is better off in the renegotiation outcome relative to her outcome without renegotiations (PBC second best). In figure 4 we see that the buyer facing the reliable (unreliable) vendor is better (worse) off relative to his *ex-ante* outside option. Finally, from figure 5, we conclude that, depending on if the prior π is low or high, the reliable vendor could be either better or worse off than her outcome under PBC second best. Essentially, the reliable type has to "subsidize" the unreliable type through the medium of the buyer.

8. Conclusions

Our analysis provides the first formal explanation for why, when engine technology is new, RBC might be the chosen contractual outcome in an after-sales environment. Along the way our analysis reveals that PBC serves as a superior signaling device compared to RBC; an aspect that we show

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

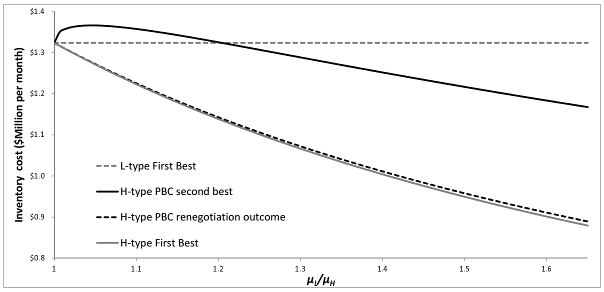

Figure 2 **Spare engine inventory costs** $(\pi = 0.5)$

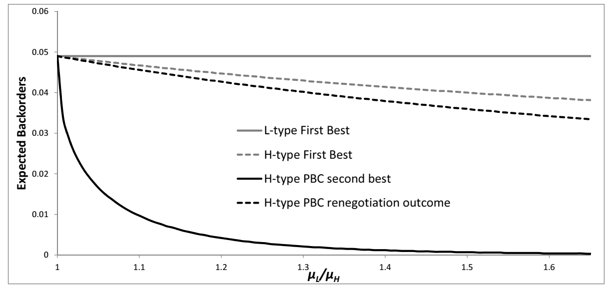

Figure 3 **Expected Backorders** $(\pi = 0.5)$

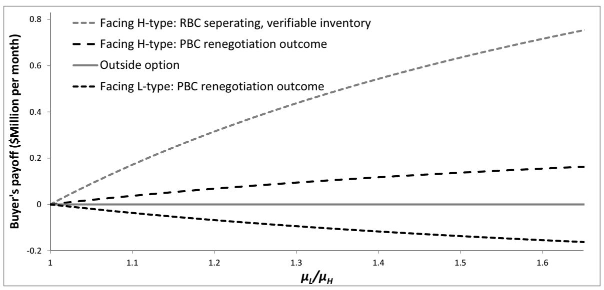

Figure 4 **Buyer's Payoffs** $(\pi = 0.5)$

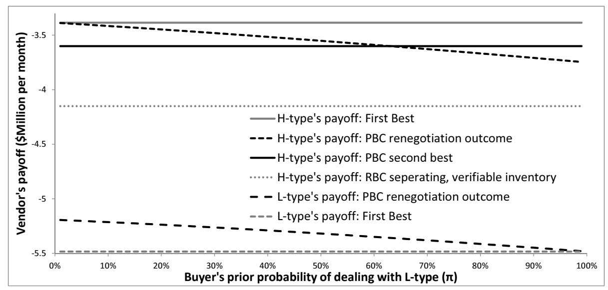

Figure 5 **Vendor's Payoffs** $(\mu_L/\mu_H = 5/3)$

to be of practical significance and which has not been identified in the literature. For the case with unverifiable inventory we find that signaling with PBC engenders a second best outcome via overinvestment in inventory; thereby indicating that greater availability could actually be bad news from an efficiency perspective. However, we identify a contractual innovation that seems practical and has the potential to restore efficiency. Such a contract has other beneficial implications: it provides greater incentive for the vendor to undertake significant R&D investment in a setting with prospective asymmetric information.[20] It is worth noting that we have derived our insights in a setting with risk neutral players, and it would be interesting to explore how these insights are affected by risk aversion of the parties involved. In summary, we believe our work advances conceptual clarity in the complex after-sales setting, but we also hope that it leads to further exploration, such as extending our treatment to a more general setting with double moral hazard; wherein the moral hazard on either end is potentially multi-dimensional.

9. Appendix A: Refinements and Pooling Equilibria

It is typical to find multiple equilibria in the analysis of signaling games as the concept of perfect Bayesian equilibrium (PBE) does not place restrictions on off-equilibrium beliefs of the players. To refine the set of PBE we rely on the "intuitive criterion" proposed by Cho and Kreps (1987). Specifically, this 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.

[20] It can cost as much as $1.5 to $2 billion to bring a new engine design to commercial viability (Mabert et al. 2006).

In what follows, $\sigma(H|\mathbf{C})$ denotes buyer's updated belief that vendor is of type H after observing contract offer $\mathbf{C}$. For type $\tau \in \{L, H\}$, the expected payoff of the vendor of type τ under contract $\mathbf{C}$ are: $V_\tau = T_\tau - cs_\tau - \mu_\tau M$, 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: $U = \sigma(H|\mathbf{C})U_H + (1-\sigma(H|\mathbf{C}))U_L$. An equilibrium contract, $\mathbf{C}$, which offers payoff $V_H(\mathbf{C})$ and $V_L(\mathbf{C})$ to the H and L-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 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: $V_L(\hat{\mathbf{C}}) < V_L(\mathbf{C})$. (A2) The H-type achieves a higher payoff in the deviation than in the proposed equilibrium: $V_H(\hat{\mathbf{C}}) > V_H(\mathbf{C})$. (A3) The participation constraint for the buyer is satisfied if he believes that the vendor is of the H-type with certainty: $U_H(\hat{\mathbf{C}}) \geq \theta$. Or such that:

(B1) 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: $V_H(\hat{\mathbf{C}}) < V_H(\mathbf{C})$. (B2) The L-type vendor achieves a higher payoff in the deviation than in the proposed equilibrium: $V_L(\hat{\mathbf{C}}) > V_L(\mathbf{C})$. (B3) The participation constraint for the buyer is satisfied if he believes that the vendor is of the L-type with certainty: $U_L(\hat{\mathbf{C}}) \geq \theta$.

The intuitive criterion eliminates all separating PBE except the *least-cost separating* equilibrium, which is our focus. Further, it generally eliminates pooling equilibria as well. For the treatment in this paper, the authors have verified that pooling equilibria are eliminated by the intuitive criterion in all cases; however, one of the pooling equilibria for RBC with verifiable inventory (§5.1) survives this refinement. (The formal proofs are available from the authors upon request.) We argue that this pooling equilibrium is not a compelling prediction of the outcome of the game.

In order to do so we rely on the idea of renegotiations, in the spirit of Beaudry and Poitevin (1993), and as described in §6.1. Note that the separating equilibrium in §5.1 is efficient, therefore a Pareto improvement is not possible, and hence the equilibrium will not be renegotiated. On the other hand, the RBC pooling equilibrium will be renegotiated. A rough intuition is as follows: any pooling equilibrium is inefficient due to the use of expected failure rate in setting inventory. Then, after signing a pooling contract and before execution, either type of the vendor will have an incentive to initiate a Pareto improving renegotiation by choosing the optimal inventory level. More precisely, condition (v) in §6.1 is violated by the RBC pooling equilibrium that survived refinement, and therefore it does not survive the renegotiation process.

10. Appendix B: 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 with respect to 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.

LEMMA 1. *For any value of $u \geq c$, it is the case that $\phi(u) := u[E_H(B|s_H(u)) - E_L(B|s_L(u))] + c(s_H(u) - s_L(u)) < 0$, 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 O_L and O_H also satisfy the EW order, then $\phi(u)$ is non-increasing.*

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

Now assume that O_L and O_H follow the EW order. Given the definitions of $s_H(u)$ and $s_L(u)$, it follows that $\int_{s_H(u)}^{\infty} (1-F_H(x))\,dx \leq \int_{s_L(u)}^{\infty} (1-F_L(x))\,dx$, or $E_H(B|s_H(u)) \leq E_L(B|s_L(u))$. Taking the derivative of $\phi(u)$ with respect to u gives $\phi'(u) = [E_H(B|s_H(u)) - E_L(B|s_L(u))] \leq 0$.$\square$

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 hazard rate ordering implies FOSD, we conclude that $\overline{s}_L > \overline{s}_H$. Further, $\overline{V}_L - \overline{V}_H = \chi[E_H(B|\overline{s}_H) - E_L(B|\overline{s}_L)] + c(\overline{s}_H - \overline{s}_L) + (\mu_H - \mu_L)(r+M) = \phi(\chi) + (\mu_H - \mu_L)(r+M)$, using Lemma 1 for $u = \chi$ and $\mu_H < \mu_L$, we conclude that: $\overline{V}_L - \overline{V}_H < 0$. $\square$

Proof of Proposition 2: In a separating equilibrium, if it exists, the vendor is able to credibly signal her type. Given that the L-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: $\max_{w_L, s_L, \alpha_L \geq 0} w_L - (1-\alpha_L)\mu_L M - cs_L$, such that $-w_L - \alpha_L\mu_L M - \chi E_L(B|s_L) - \mu_L r \geq \theta$. The constraint will be binding at optimum (otherwise the vendor can increase the fixed fee w_L and improve her payoff), therefore $w_L^* = -\alpha_L\mu_L M - \chi E_L(B|s_L) - \mu_L r - \theta$, and the objective becomes $\max_{s_L, \alpha_L \geq 0} -\chi E_L(B|s_L) - \mu_L(r+M) - \theta - cs_L$. This function does not depend on α_L and is concave in s_L, therefore, the optimal inventory to keep is equal to the first-best level, i.e., $s_L^* = \overline{s}_L$. The unreliable vendor makes her first-best payoff, $\overline{V}_L$.

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

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

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

Case B: (IR$_H$) is binding. This case does not contain any further solutions.

In what follows, $\sigma(H|\mathbf{C})$ denotes buyer's updated belief that vendor is of type H after observing contract offer $\mathbf{C}$. A belief structure that supports these equilibria, is: $\sigma(H|(w^*_H,\alpha^*_H,s^*_H))=1$, $\sigma(H|(w,\alpha,s))=0$, if $(w,\alpha,s)\neq(w^*_H,\alpha^*_H,s^*_H)$. Such a belief structure ensures that neither type of the vendor has any incentive to deviate unilaterally from this equilibrium.□

Proof of Proposition 3: We consider the possibility of recovering first-best rents in a separating equilibrium – (w^*_H,v^*_H,s^*_H) and (w^*_L,v^*_L,s^*_L). Since inventory is observable and verifiable it is straightforward to contract on its first-best levels – $\overline{s}_H$ and $\overline{s}_L$. However, the transfer payments need to adhere to the incentive compatibility (IC_τ) and participation constraints (IR_τ) for $\tau\in\{L,H\}$. Consider the following contract parameters $w^*_H=-\theta-\mu_H r+(v^*_H-\chi)E_H(B|\overline{s}_H)$, $w^*_L=-\theta-\mu_L r+(v^*_L-\chi)E_L(B|\overline{s}_L)$. Plugging the appropriate values in the LHS of (IR$_H$) and (IR$_L$), we obtain $-w^*_H+(v^*_H-\chi)E_H(B|\overline{s}_H)-\mu_H r=\theta+\mu_H r-(v^*_H-\chi)E_H(B|\overline{s}_H)+(v^*_H-\chi)E_H(B|\overline{s}_H)-\mu_H r=\theta$, $-w^*_L+(v^*_L-\chi)E_H(B|\overline{s}_L)-\mu_L r=\theta+\mu_L r-(v^*_L-\chi)E_L(B|\overline{s}_L)+(v^*_L-\chi)E_L(B|\overline{s}_L)-\mu_L r=\theta$. 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$_H$). Plugging in the appropriate values, we obtain $v^*_L\left[E_L(B|\overline{s}_L)-E_H(B|\overline{s}_L)\right]\leq\chi[E_L(B|\overline{s}_L)-E_H(B|\overline{s}_H)]+(\mu_L-\mu_H)r+c(\overline{s}_L-\overline{s}_H)$. Similarly,

(IC_L) implies $v_H^*\left[E_H(B|\bar{s}_H) - E_L(B|\bar{s}_H)\right] \geq \chi[E_L(B|\bar{s}_L) - E_H(B|\bar{s}_H)] + (\mu_L - \mu_H)r + c(\bar{s}_L - \bar{s}_H)$. The conditions above are satisfied for any: $v_L^*\left[E_L(B|\bar{s}_L) - E_H(B|\bar{s}_L)\right] \leq \chi[E_L(B|\bar{s}_L) - E_H(B|\bar{s}_H)] + (\mu_L - \mu_H)r + c(\bar{s}_L - \bar{s}_H) \leq v_H^*\left[E_L(B|\bar{s}_H) - E_H(B|\bar{s}_H)\right]$. Furthermore, such v_H^* and v_L^* always exist and are non-negative. To see this, note that the hazard rate ordering between O_L and O_H implies FOSD, and therefore: $[E_L(B|\bar{s}_L) - E_H(B|\bar{s}_L)] \geq 0$, $[E_L(B|\bar{s}_H) - E_H(B|\bar{s}_H)] \geq 0$ and $\chi[E_L(B|\bar{s}_L) - E_H(B|\bar{s}_H)] + (\mu_L - \mu_H)r + c(\bar{s}_L - \bar{s}_H) > 0$ due to Lemma 1 and $\mu_L > \mu_H$.

A belief structure for the buyer, that supports these equilibria, is: $\sigma(H|(w_H^*, v_H^*, s_H^*)) = 1$, $\sigma(H|(w, v, s)) = 0$, if $(w, v, s) \neq (w_H^*, v_H^*, s_H^*)$. The buyer's belief structure ensures that neither type has any incentive to deviate unilaterally from this equilibrium. □

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 L-type vendor achieves first-best by setting $v_L^* = \chi$ and $w_L^* = -\mu_L r - \theta$ and for the H-type at least (IR_H) or (IC_L) need to be binding at optimum.

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

Case B: (IR_H) is binding. This case does not contain any further solutions.

In what follows, $\sigma(H|\mathbf{C})$ denotes buyer's updated belief that vendor is of type H after observing contract offer $\mathbf{C}$. A belief structure that supports these equilibria, is: $\sigma(H|(w_H^*, v_H^*)) = 1$,

$\sigma(H|(w,v))=0$, if $(w,v)\neq(w_H^*,v_H^*)$. The buyer's belief structure is such that neither type has any incentive to deviate unilaterally from this equilibrium. $\square$

Proof of Proposition 6: Recall that for $\tau\in\{L,H\}$, $V_\tau=w-vE_\tau(B|s_\tau(v))-cs_\tau(v)-\mu_\tau M$; and $U_\tau=-w+(v-\chi)E_\tau(B|s_\tau(v))-\mu_\tau r$; where inventory is $s_\tau(v)=F_\tau^{-1}\left(1-\frac{c}{v}\right)$. Then, $\frac{\partial U_\tau}{\partial w}=-1$; $\frac{\partial U_\tau}{\partial v}=E_\tau(B|s_\tau(v))-(v-\chi)\frac{c}{v^2}\frac{1-F_\tau(s_\tau(v))}{f_\tau(s_\tau(v))}$; $\frac{\partial V_\tau}{\partial w}=1$; and $\frac{\partial V_\tau}{\partial v}=-E_\tau(B|s_\tau(v))$. Under condition (1) (i.e. $E_L(B|s_L)>E_H(B|s_H)$), it is straightforward to verify that Assumption 3B (Case RS) in Beaudry and Poitevin (1993) (essentially single crossing property for the vendor's payoff) is satisfied. Using the hazard rate order and increasing hazard rate property, Assumption 3A in Beaudry and Poitevin (1993) is also satisfied provided $v\geq\chi$. We verify that $v<\chi$ is never an equilibrium outcome, hence we can explicitly restrict the parameter space to $v\geq\chi$. Consequently the conditions for Proposition 3 in Beaudry and Poitevin (1993) are met, and we can conclude that the renegotiation proof contracts are unique with respect to payoff.

We now solve for the contract parameters, following the scheme laid out in Proposition 3 of Beaudry and Poitevin (1993). Also, we define $F_p(.)=\pi F_L(.)+(1-\pi)F_H(.)$ with corresponding interpretation for μ_p and $E_p(B|s(v))=\pi E_L(B|s_L(v))+(1-\pi)E_H(B|s_H(v))$. We first solve for the reliable vendors contract parameters as follows: $\max_{w,v}\left[w-vE_H(B|s_H(v))-cs_H(v)-\mu_H M\right]$, subject to (IR): $-w+(v-\chi)E_p(B|s(v))-\mu_p r\geq\theta$. Clearly (IR) is binding at optimality, otherwise an increase in w will improve the objective. Therefore $w_H^*=(v-\chi)E_p(B|s(v))-\mu_p r-\theta$. Plugging this back into the objective function and taking FOC, we obtain: $\frac{(v-\chi)c}{v^2}\left((1-\pi)\frac{1-F_H(s_H(v))}{f_H(s_H(v))}+\pi\frac{1-F_L(s_L(v))}{f_L(s_L(v))}\right)=\pi\left(E_L(B|s_L(v))-E_H(B|s_H(v))\right)$. Since the RHS is always positive for finite v, then for the equation to have a finite solution it must be the case that $v_H>\chi$, thereby resulting in inefficiency.

Next we characterize the unreliable vendor's contract parameters by solving the following optimization problem: $\max_{w,v}\left[w-vE_L(B|s_L(v))-cs_L(v)-\mu_L M\right]$, subject to: $-w+(v-\chi)E_L(B|s_L(v))-\mu_L r\geq -w_H^*+(v_H^*-\chi)E_L(B|s_L(v_H^*))-\mu_L r$; and $-w+(v-\chi)E_p(B|s(v))-\mu_p r\geq\theta$. We ignore the second constraint and verify that is satisfied at optimality. As before, the first constraint is clearly binding at optimality, which can be written as $w_L^*=(v-\chi)E_L(B|s_L(v))+(1-\pi)(v_H^*-\chi)\left(E_H(B|s_H(v_H^*))-E_L(B|s_L(v_H^*))\right)-\mu_p r-\theta$. Plugging this back into the objective function, we are left with the residual optimization problem: $\min_v\left[cs_L(v)+\chi E_L(B|s_L(v))\right]$ which has a unique minimum at $v_L^*=\chi$. Finally, using (1) we have $E_L(B|s_L(\chi))>E_H(B|s_H(\chi))$ which implies that the other second constraint, $-w_L^*+(v_L^*-\chi)E_p(B|s(v))-\mu_p r\geq\theta$, is satisfied. $\square$

Proof of Proposition 7: In a separating equilibrium (if it exists) the vendor is able to credibly signal his type. The best the L-type vendor can do is extract all the surplus of the buyer by setting $v_L^*=\chi$ and $w_L^*=-\mu_L r-\theta-\alpha_L M\mu_L$ for any α_L. His inventory is given by $s_L(x)=F_L^{-1}\left(1-\frac{c}{x}\right)=\overline{s}_L$. The H-type's problem is then characterized by $\max_{w_H,v_H,\alpha_H} w_H-v_H E_H\left[B|s_H(v_H)\right]-cs_H(v_H)+$

$\alpha_H M\mu_H$, subject to (IR$_H$): $-w_H + (v_H - \chi)E_H\left[B|s_H(v_H)\right] - \mu_H r - \alpha_H M\mu_H \geq \theta$, (IC$_H$): $w_H - v_H E_H\left[B|s_H(v_H)\right] - cs_H(v_H) + \alpha_H M\mu_H \geq -\mu_L r - \theta - \alpha_L M\mu_L - \chi E_H\left[B|s_H(\chi)\right] - cs_H(\chi) + \alpha_L M\mu_H$, and (IC$_L$): $-\mu_L r - \theta - \chi E_L\left[B|s_L(\chi)\right] - cs_L(v_L) \geq w_H - v_H E_L\left[B|s_L(v_H)\right] - cs_L(v_H) + \alpha_H M\mu_L$, where his inventory decision $s_H(v)$ given the performance based penalty $v \geq c$ is characterized by $s_H(v) = F_H^{-1}\left(1 - \frac{c}{v}\right)$. We conjecture that a contract with the following parameters constitutes a separating equilibrium that extracts first-best rents $v_H = v_L = \chi$, $\alpha_H \leq -\frac{r}{M} \leq \alpha_L$; $\alpha_H < \alpha_L$, $w_H = -\alpha_H(M\mu_H + r) - \chi E_H\left[B|s_H(\chi)\right] - \theta$, $w_L^* = -\mu_L r - \theta - \alpha_L M\mu_L$. 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$_H$) is binding, therefore the vendor extracts all rents. Finally the conditions placed on α_H and α_L ensure that both ICs are satisfied, without necessarily resulting in a pooling contract. In what follows, $\sigma(H|\mathbf{C})$ denotes buyer's updated belief that vendor is of type H after observing contract offer $\mathbf{C}$. A belief structure that supports these equilibria, is: $\sigma(H|(w_H^*, \alpha_H^*, v_H^*)) = 1$; $\sigma(H|(w, \alpha, v)) = 0, \text{if } (w, \alpha, v) \neq (w_H^*, \alpha_H^*, v_H^*)$. Such a belief structure ensures that neither type has any incentive to deviate unilaterally from this equilibrium.$\square$

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