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Value of Audit for Supply Chains with Hidden Action and Information

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Outsourcing can provide firms with a competitive advantage by realizing the benefits of suppliers' low labor, better quality and improved innovation. Yet, the supply chain managers have several concerns about outsourcing which are mainly due to lack of critical information regarding the actions of their suppliers. In this paper, we study the effectiveness of auditing the supplier's hidden actions for the buyer (principal) when the supplier (agent) is privately informed about the extent of the supply risk. In order to accomplish this, we first extend the standard principal-agent model by considering a case in which the agent's hidden action affects the extent of information asymmetry between principal and agent. By comparing the agency costs associated with the optimal menu of contracts with and without audit, we then completely characterize the value of audit from the perspectives of both buyer and supplier as well as total supply chain. First, the analysis of value of audit from the buyer's perspective shows that the buyer can strictly benefit from auditing the supplier's actions. Second, we find that not only the buyer but also the supplier can strictly benefit from an audit. Third, the audit enables the buyer to customize her contract offerings based on the reliability of the supplier. Finally, by analyzing the impact of problem parameters on the value of the audit, we identify the conditions under which an audit would be beneficial for individual supply chain parties as well as the overall supply chain.

Key words: Cost benefit analysis; Supply contracts; Adverse selection; Moral hazard; Audit

1. Introduction

Globalization leveled the playing field for the supply chains long ago but observing the supplier's actions in distant locations still remains significant challenge for many companies. After multiple incidences including different Boeing 787s emergency landings due to on-board fires, on January 16, 2013, the Federal Aviation Administration (FAA) issued an emergency directive ordering all US-based airlines to ground their Boeing 787s until further notice. Further investigations [NY Times 26 January 2013] reveal that the electrical fires were caused by Lithium-Ion batteries whose production was subcontracted by Thales, the French company responsible for the 787's electrical systems, to a tier-2 supplier in Asia, which was also approved by Boeing. The groundings cost Boeing an estimated $600 million USD, halted deliveries and forced some airlines to lease alternative airplanes. Boeing may have financial resources to recover from this but such incidences would be detrimental for many companies, particularly those that are aggravated by reduced visibility regarding both the true risk and actions of suppliers that are just a few links away in the supply chain. Indeed, surveys suggest that more than 40% of companies lack this visibility, even into their tier-1 suppliers, and the percentage increases to 75% for tier-2 suppliers [Industry Week December 2009]. This information asymmetry can be the result of insufficient due diligence on the part of the buyer, or the result of suppliers not taking certain actions (e.g., skipping a certain testing process as in the Boeing case) without informing the buyer. Such increased information asymmetry due to a lack of control is also one of the primary reasons behind problems in IT system outsourcing [Forbes 2016] as well as the toys, textiles and electronics industries [USA Today October 2008]. In another study that surveyed high-ranking supply chain executives across the United States (Rogers 2009), the lack of control over key suppliers stands out as one of the greatest obstacles in improving supply-chain risk management at their companies. These cases also indicate that a lack of control and supply visibility (or lack thereof) not only creates supply chain-related performance shortfalls, but also have had negative effects on companies' financial performance within the past five years (Hendricks and Singhal 2005). The main goal of this paper, therefore, is to shed light on the issues caused by the lack of control and visibility regarding the upstream supplier's actions and to explore the various means with which the resulting adverse effects can be mitigated.

As showcased by the above cases, a particularly important issue that faces a downstream buyer is to find out how to incentivize suppliers to take the costly actions to improve the reliability of their processes in the presence of information asymmetry. Numerous approaches with varying degrees of control and visibility have been proposed in both practitioner and academic circles (Dyer et al. 1998). One common approach in this case is to use a performance-based contract. This has the benefit of minimizing the costs and maximizing the bargaining power for the sake of buyers. Another approach is to audit the actions of the supplier throughout every phase of the production process. The second approach provides the buyers with more transparency into the actions of their suppliers, but at the same time, makes it more costly for them to establish and, more importantly, maintain such a close relationship with their suppliers. There is some variation in the adoption of these mechanisms among the supply chain companies (Spekman et al. 1998). Even the same company may change its strategy over the time. For example, consider the case of Apple, which to a large extent, owns its success to its extensive contract-based outsourcing program [NY Times 21 January 2012]. However, as indicated in its 2019 report [Apple Inc. 2019], Apple seems to increase its degree of control over its suppliers by implementing a very strong auditing program. In just 2018 alone, Apple completed 770 managed supplier assessments covering manufacturing facilities, logistics and repair centers, and contact center facilities. Not only the users of contract-based buyers like Apple but also OEMs that run extensive supplier networks have increased their auditing efforts in order to preempt the publicity smear due to possible noncompliance of their suppliers. For example, an extensive audit program undertaken by Toyota after having to recall around 8 million vehicles due to malfunctioning gas pedals between 2009 and 2010 uncovered another covert action incidence for one of Toyota's component suppliers [see Bloomberg Business Week report, Kitamura et al. October 2010].

Motivated by this variation, in this paper, we study the value of audit by comparing the following two mechanisms in the presence of hidden information, the extent of which is affected by the hidden action of the supplier: (*i*) in the first one, the buyer incentivizes the supplier to take a particular action by offering a performance-based contract (hereafter referred to as "Induced-Effort (IE) contract"); and; (*ii*) in the second one, the buyer incurs a cost to audit the supplier's hidden action (hereafter referred to as "Audited-Effort (AE) contract"). By comparing these two settings, our aim is to study the following research questions:

Research Question 1: What is the value of audit in this context for the buyer, the supplier and the total supply chain?

Research Question 2: How do the problem parameters (i.e., supplier's hidden information and cost of hidden action) affect the value of audit for each supply chain party and total supply chain?

This paper contributes to the literature in two ways. First one is methodological in nature. It is commonly accepted in the principal-agent literature that under the standard setting (i.e., both principal and agent are risk-neutral, and the agent is not protected by limited liability constraints) the moral hazard constraints have no impact on the principal's payoff (see Laffont and Tirole 1993, Laffont and Martimort 2002 and the citations therein). This implies that auditing the agent's hidden action does not generate any value for the principal. This paper adds to this result a caveat. Specifically, we show that if the hidden actions exerted by the agent affects the degree of information asymmetry between principal and agent, then observing hidden action of the agent can strictly increase the principal's payoff.

This has significant implications for supply chains that are subject to disruption risk, the extent of which can be affected by the hidden actions taken by the upstream supplier. This constitutes our *second contribution*. Applying our result to the supply chain setting, we completely characterize the value of auditing the hidden action of the upstream supplier from the perspective of the downstream buyer as well as the total supply chain and show when it can be a win-win strategy for all parties involved.

The remainder of the paper is structured as follows: first, we review the existing relevant literature in §2. The modeling approach and assumptions will be discussed in §3. In section §4, we characterize the optimal contract under full information scenario. The optimal Induced-Effort and Audited-Effort contracts under information asymmetry are characterized in §§5 and 6, respectively. In §7, we identify the value of audit for the buyer and supplier as well as whole channel. Finally, §8 concludes the paper.

2. Literature Review

Our paper is related to two streams of research in operations management. The first one focuses on modeling improvement decisions of supply chain firms. The second stream relates to contract design under supply disruption. In what follows, we review each stream and relate them to our work.

The papers in the first stream vary in terms of whether the decision taken by the firm improves the quality of the product (Baiman et al. 2000, Balachandran and Radhakrishnan 2005, Chao et al. 2009, Babich and Tang 2012, Hsieh and Liu 2010, Nikoofal and Gümüş 2018, Quigley et al. 2018, Zhang et al. 2019), reduces cost (Corbett et al. 2005, Bernstein and Kok 2009, Li 2012, Iida 2012, Kim and Netessine 2013), or increases the reliability of the process (Chopra et al. 2007, Wang et al. 2010, Tang et al. 2013). Clearly, our paper is more related to the latter stream because the supplier's action may increase the supply chain reliability. First of all, in some of the above papers it is assumed that the action taken by the firm cannot be observed by the other party in the supply chain, hence, the problem becomes a moral hazard type. However, in our model, the supplier's action affects the degree of information asymmetry between parties, hence it models adverse selection followed by moral hazard.

Second, some of the above papers assume that both supply chain parties are, ex-ante, in equal footing in terms of information available to them, and the action taken collaboratively by the parties creates ex-post information asymmetry among them. However, in our model, supply chain parties are endowed with asymmetric information with regards to the extent of [supply] uncertainty in both ex-ante and ex-post stages and the cost of action is incurred only by the supplier. Finally, our paper is different in terms of the research questions it aims to answer. Namely, our paper aims to explore the impact of auditing the supplier's action in reducing the degree of information asymmetry about the supply disruption risk.

The papers in the second stream study hidden information problems in a supply chain context (see Cachon 2003 for an excellent review of this literature). Similar to the first stream, the papers in this stream can also be categorized in terms of whether the hidden information is defined in terms of the supplier's cost (e.g., Corbett et al. 2004, Cachon and Zhang 2006, Özer and Raz 2011, Kim and Netessine 2013) or reliability (e.g., Yang et al. 2009, Tomlin 2009, Chaturvedi and Martinez-de Albeniz 2011, Lee et al. 2013, Gümüş et al. 2012, Sainathan and Groenevelt 2019). Our paper contributes to the latter case by developing a supply chain reliability model that explores how audit can be combined with the contracts to effectively reduce the agency costs associated with hidden information and hidden action. In this regard, our paper is related to the growing body of literature that studies the impact of audit in buyer-supplier relationship under supplier responsibility risk (Chen and Lee 2016, Chen et al. 2019), supplier adulteration risk (Lee and Li 2018, Babich and Tang 2012), and supplier environmental responsibility risk (Plambeck and Taylor 2015). Our paper differs from those in this stream mainly for two reasons. First, we consider supplier's hidden action on top of his private information. Second, most of the papers analyze the effectiveness of contingency tactics (e.g., backup production option or inventory storage), which can be employed by the supplier in the case of disruption, however, we evaluate the effectiveness of process improvement, which is a mitigation tactic that stochastically reduces the exposure to disruption.

Finally, our paper is related to the mixed model of adverse selection followed by moral hazard in economics. To distinguish our paper from those in the economics literature, we recognize two different approaches that jointly explore the issues caused by hidden information and hidden action depending on whether the agent's hidden action has a *deterministic* or *stochastic* effect on the hidden information. The deterministic relation between moral hazard and adverse selection has been extensively discussed in the economics literature in the context of procurement models (refer to Laffont and Tirole (1993), Laffont and Martimort (2002) and the references therein). Note that the key difference between stochastic and deterministic models lies in the nature of the links between an agent's action, an agent's type, and the contractual variables available to the principal. Specifically, in the traditional procurement models discussed in Laffont and Tirole (1986, 1993), the agent's type (i.e., hidden information) is defined as her *ex-ante* marginal cost, and the cost reduction effort (i.e., hidden action) that she exerts reduces the *ex-post* marginal cost that is observable and contractible by the principal. This problem is called the *false moral hazard* model because one can rewrite the agent's action in terms of a deterministic function of the agent's type and contract variables to eliminate the moral hazard component (please refer to Laffont and Martimort (2002)). In our model, however, the observable and contractible variable is the supplier's production outcome, the extent of which depends on both the agent's type (reliability) and action (process improvement effort). Furthermore, the supplier's action has a stochastic effect on his type (i.e., *ex-post* reliability) via a known probability distribution function. Therefore, we cannot simply express the supplier's action in terms of his type and the contractual variable. The mere fact that the effort exerted by the supplier has a stochastic effect on its reliability is not sufficient to explain why moral hazard has an actual effect on the buyer's payoff. Therefore, we also need to explore the difference between our modeling approach and the stochastic models discussed in the literature. In this sense, our paper is related to the models through the stochastic relationship between moral hazard and adverse selection that has been extensively explored by Laffont and Martimort (2002). Similar to our model, the effects of type and effort on the contract variables are stochastic in Laffont and Martimort (2002); however, in contrast to our results, the moral hazard does not have any actual effect on the principal's payoff. The reason behind this difference lies in the crucial assumption made in Laffont and Martimort (2002) that the hidden action exerted by the agent does not change the information asymmetry between different agent types. As we previously discussed, the process improvement effort exerted by the supplier in our model may stochastically increase the survival probability. Hence, the supplier's relaibility (i.e., hidden information) at the *ex-post* stage may be different from that at the contracting stage. In other words, different from the models in the literature, the agent's action changes the degree of information asymmetry between the principal and agent in our modeling approach.

3. Model Framework

Consider a stylized two-level supply chain model with a buyer (hereinafter referred to as ”she”) and a risky supplier (referred to as ”he”). At the downstream level, the buyer faces a unit demand D and earns $\$b$ per unit sold in the market. To satisfy her demand, she needs to procure from a supplier whose production cost is $\$c$ per unit. In order to focus on the supply-side risks, we assume that the demand is known at the time of the contract and, without loss of generality, we normalize it to be one, i.e., $D = 1$. At the upstream level, the supplier is unreliable in the sense that his ultimate production quantity $\tilde{q}$ is subject to a disruption risk. The extent of disruption risk depends on exogenous and endogenous factors, both of which are unobservable by the buyer. The exogenous factor faced by the supplier is determined by his true reliability type denoted by θ. For the sake of analytical tractability, we assume that θ can take two values: r (reliable) and u (unreliable) representing r- and u-type suppliers, respectively. We assume that the buyer has *a priori* beliefs about the type of supplier, denoted by $\nu \in [0,1]$, in the sense that the fractions of the r- and u-type suppliers are ν and $1-\nu$, respectively. Everything else remaining the same, the r-type supplier is less likely to face supply disruption than the u-type one in the sense of first-order stochastic dominance. Second, we consider endogenous factors that can be actively managed by the supplier to reduce the likelihood of disruption. Specifically, the θ-type supplier can exert a *process improvement effort* denoted by $e_\theta \in \{0,1\}$ to decrease the likelihood of disruption. We normalize the cost of no effort at zero and the cost of effort at ψ_θ, where $\theta \in \{r,u\}$. Note that such an effort is not observable by the buyer and, hence, causes the moral hazard problem. Finally, we assume that the supplier's production outcome denoted by $p(q_\theta = 1 \mid \theta, e_\theta)$ is a function of his reliability $\theta \in \{u,r\}$ and process improvement effort $e_\theta \in \{0,1\}$, as provided in Table 1.

Table 1 Success probability $p(q_\theta = 1 \mid \theta, e_\theta)$ as a function of supplier type and his process improvement

		supplier's reliability (type)	
		$\theta = u$	$\theta = s$
Process	$e_\theta = 0$	$p(u \mid 0) = \varphi_u$	$p(r \mid 0) = \varphi_r$
improvement	$e_\theta = 1$	$p(u \mid 1) = \rho_u$	$p(r \mid 1) = \rho_r$

Without loss of generality, we equalize the increase in the reliability observed by both supplier types given the process improvement effort, that is, $\rho_r - \varphi_r = \rho_u - \varphi_u = \delta$. The following two conditions characterize the impact of the supplier's type and effort on the likelihood of disruption: (i) for the same level of effort, $e_r = e_u = e \in \{0,1\}$, the reliability of the r-type is larger than that of the u-type, that is, $\rho_r \geq \rho_u$ and $\varphi_r \geq \varphi_u$; and (ii) the likelihood of disruption for both u- and r-type suppliers increases in e, that is, $\rho_\theta \geq \varphi_\theta$. These conditions are commonly referred to as ”Spence-Mirrlees Conditions” (Laffont and Martimort 2002) in economics.

Using this modeling framework, we evaluate two different contractual strategies for the buyer to analyze the value of an audit. In the first strategy, that is, the IE (*Induced-Effort*) contract, the buyer

cannot observe the supplier's process improvement effort and, hence, indirectly influences his decisions via contract terms. In the second strategy, i.e., the AE (*Audited-Effort*) contract, the buyer can monitor the supplier's effort in exchange for an auditing cost of $\mathscr{A}$. Even though the two contractual strategies differ in terms of the availability of information regarding the supplier's decisions, both contracts share a common form that consists of three terms: (i) upfront transfer payment $\$U_\theta$, (ii) reward $\$X_\theta$, and (iii) rebate $\$\xi_\theta$. The first term is a fixed payment irrespective of the quantity outcome q_θ, whereas the second and third terms stand for the reward payment (from the buyer to the supplier) and rebate payment (from the supplier to the buyer) that depend on the realizations of $q_\theta = 1$ and $q_\theta = 0$, respectively. This contract encompasses different contracts as special cases. For example, a two-term contract can be represented by either $X_\theta = 0$ or $\xi_\theta = 0$, whereas a fixed-term (resp., contingent) contract corresponds to the case in which both $X_\theta = 0$ and $\xi_\theta = 0$ (resp., $U_\theta = 0$).
For the expositional convenience, we list the notation for all parameters and decisions in Table 2.

Table 2 List of notations

Parameters and Decision variables	
b	Buyer's revenue per unit sold in the market
c	Supplier's marginal production cost
$\theta \in u, r$	Supplier's reliability type which can be reliable (r-type) or unreliable (u-type)
ν	Buyer's a priori belief that the supplier is of r-type
$q_\theta \in \{0,1\}$	θ-type supplier production outcome which can be successful ($q_\theta = 1$) or failure ($q_\theta = 0$)
ρ_θ	Success probability (i.e., $q_\theta = 1$) if θ-type supplier invests in process improvement ($e_\theta = 1$)
φ_θ	Success probability (i.e., $q_\theta = 1$) if θ-type supplier does not invest in process improvement ($e_\theta = 0$)
ψ_θ	Cost of process improvement for the θ-type supplier
$\mathscr{A}$	Cost of audit for the buyer
$e_\theta \in \{0,1\}$	Level of process improvement effort exerted by the θ-type supplier
U_θ	Upfront transfer payment from buyer to θ-type supplier
X_θ	Reward payment from the buyer to the θ-type supplier if $q_\theta = 1$
ξ_θ	Rebate payment from the θ-type supplier to the buyer if $q_\theta = 0$

The timing of events and actions is as follows. At time zero, nature reveals the supplier's true level of reliability, that is, $\theta \in \{u, r\}$, only to the supplier. The buyer offers a menu of contracts $(U_\theta, X_\theta, \xi_\theta)$ for the $\theta \in \{u, r\}$. The θ-type supplier may accept or reject the contract. If the supplier accepts the contract, he decides whether to exert process improvement effort, that is, $e_\theta \in \{0,1\}$. If the AE contract has been offered, then the buyer incurs an auditing cost of $\mathscr{A}$ and observes the supplier's effort. Finally, the production outcome $q_\theta \in \{0,1\}$ is realized, and the contract is executed according to its terms. The supplier's and the buyer's profits are summarized in Table 3.

Table 3 buyer's and supplier's profits

		buyer's profit	supplier's profit
supplier's	$e_\theta = 0$	$\varphi_\theta b - U_\theta - \varphi_\theta X_\theta + (1-\varphi_\theta)\xi_\theta$	$U_\theta - c + \varphi_\theta X_\theta - (1-\varphi_\theta)\xi_\theta$
effort	$e_\theta = 1$	$\rho_\theta b - U_\theta - \rho_\theta X_\theta + (1-\rho_\theta)\xi_\theta$	$U_\theta - c - \psi_\theta + \rho_\theta X_\theta - (1-\rho_\theta)\xi_\theta$

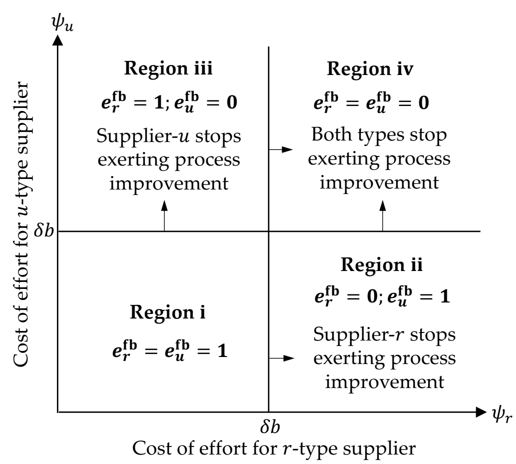
4. First-Best Solution

As a benchmark, in this section, we assume that the supplier's reliability θ is known and his choice of process improvement e_θ is observable by the buyer. Given the contract $(U_\theta, X_\theta, \xi_\theta)$ offered by the buyer, the supplier takes action e_θ^{fb}, where superscript "fb" indicates the first-best level of effort. Note that by observing both the supplier's reliability type and decision, the buyer can offer a contract that satisfies only the θ-type supplier's participation constraint. Therefore, she pays no rent to the supplier and extracts all the channel profits. The following Proposition 1 characterizes the optimal effort that the buyer wants to induce on the θ-type supplier (note that the proofs for all of the propositions are presented in the Appendix).

Proposition 1. *Under first-best conditions, the buyer induces process improvement effort on the supplier if* $(\rho_\theta - \varphi_\theta)b \geq \psi_\theta$. *Furthermore, the first-best contract that implements this effort is fully characterized in Table 4.*

Table 4 Buyer's optimal contract and supplier's first-best effort under symmetric information

Region	Optimal contracts $(U_r, X_r, \xi_r), (U_u, X_u, \xi_u)$	supplier's first-best level of effort
i. $\psi_r \leq \delta b; \psi_u \leq \delta b$	$(c+\psi_r, 0, 0), (c+\psi_u, 0, 0)$	$e_r^{\text{fb}} = 1, e_u^{\text{fb}} = 1$
ii. $\psi_u \leq \delta b < \psi_r$	$(c, 0, 0), (c+\psi_u, 0, 0)$	$e_r^{\text{fb}} = 0, e_u^{\text{fb}} = 1$
iii. $\psi_r \leq \delta b < \psi_u$	$(c+\psi_r, 0, 0), (c, 0, 0)$	$e_r^{\text{fb}} = 1, e_u^{\text{fb}} = 0$
iv. $\delta b < \psi_r; \delta b < \psi_u$	$(c, 0, 0), (c, 0, 0)$	$e_r^{\text{fb}} = 0, e_u^{\text{fb}} = 0$



There are three takeaways from Proposition 1. First, note that the optimal contract is a fixed-term contract (i.e., both $X_\theta = 0$ and $\xi_\theta = 0$). This observation is aligned with the contract design literature that shows that fixed-term contracts are theoretically the best in terms of achieving overall system efficiency (Laffont and Tirole 1993). Second, under the fixed-term contract, the supplier's objective is aligned with total channel profits; hence, he internalizes both the cost and the benefit of the process improvement effort on the channel. The cost of the process improvement effort is ψ_θ. The benefit comes from the increase in survival probability given the process improvement decision, that is, $\delta = \rho_\theta - \varphi_\theta$ multiplied by the profit earned per unit sold in the market, b. To summarize, as long as the cost ψ_θ is less than the (expected) benefit δb, the supplier exerts the process improvement effort. Finally, we note that because we do not impose limited liability constraints for the supplier and assume that all parties are risk-neutral, the standard results of principal–agent models imply that Proposition 1 can also be extended to a pure moral hazard setting in which the buyer observes the true reliability type (but not the action) of the supplier (Laffont and Martimort 2002). In the next two sections, we analyze the optimal menu of contracts under IE and AE. We then characterize the value of an audit for the buyer and supplier as well as the entire channel by comparing each party's profit under IE and AE contracts.

5. Induced-Effort (IE) Contract

In this section, we characterize the optimal menu of contracts for the IE setting that induces a specific process improvement effort on each supplier type. Note that because both the supplier's type and action are unobservable by the buyer, IE gives the optimal contract under the mixed model of adverse selection followed by moral hazard. Using backward induction, one first needs to characterize the supplier's process improvement decision. The θ-type supplier decides on the process improvement effort by solving the following equation:

$$\pi_S^\theta\left(U_\theta, X_\theta, \xi_\theta \mid e_\theta\right) = \max_{e_\theta \in \{0,1\}} \left\{U_\theta + p\left(\theta \mid e_\theta\right) X_\theta - \left(1 - p\left(\theta \mid e_\theta\right)\right)\xi_\theta - \left(c + e_\theta \psi_\theta\right)\right\} \tag{1}$$

where the first three terms denote the expected net payment transferred between the buyer and the θ-type supplier, and the last term denotes the cost incurred by the supplier. Note that by exerting effort, the supplier stochastically increases the likelihood of survival; however, he must incur an additional cost ψ_θ that depends on his type. The following lemma characterizes θ-type supplier's best response function:

Lemma 1. *Given a contract $(U_\theta, X_\theta, \xi_\theta)$ offered by the buyer, the θ-type supplier exerts process improvement effort, that is, $e_\theta^*(U_\theta, X_\theta, \xi_\theta) = 1$ iff $X_\theta + \xi_\theta \geq \frac{\psi_\theta}{\delta}$.*

As opposed to the full information scenario, fixed-term contracts are no longer sufficient to induce a process improvement effort on the supplier under asymmetric information. As shown in this lemma, the buyer must provide a θ-type supplier with the right amount of incentive fees via reward (contingent payment) X_θ and/or rebate (penalty) ξ_θ terms. Note that the net incentive observed by the θ-type supplier (which also measures the incentive power of the IE contract; see Laffont and Tirole 1993) equals $X_\theta + \xi_\theta$. Therefore, he exerts the process improvement effort as long as the power of the contract is more than the per-unit reliability improvement cost, that is, $\frac{\psi_\theta}{\delta}$. Additionally, note that the buyer must set $X_\theta + \xi_\theta = b$ if she wants to induce the first-best (i.e., channel efficient) effort decision on the supplier. However, as we subsequently observe, this situation is not always aligned with the buyer's incentives, which in turn distorts the efficiency of the entire channel.

With the assistance of Lemma 1, we can now formulate the buyer's optimal contract design problem. First, the optimal menu of contracts needs to satisfy the following individual rationality (IR) constraints to ensure a non-zero profit for the θ-type supplier:

$$\pi_S^\theta\left(U_\theta, X_\theta, \xi_\theta \mid e_\theta^*\right) = p\left(\theta \mid e_\theta^*\right) X_\theta - \left(1 - p\left(\theta \mid e_\theta^*\right)\right) \xi_\theta + \left(U_\theta - c - e_\theta^* \psi_\theta\right) \geq 0,\, \theta \in \{u, r\} \tag{2}$$

where e_θ^* denotes the θ-type supplier's effort provided that the buyer offers a menu of contracts $(U_\theta, X_\theta, \xi_\theta)$, that is,

$$e_\theta^* = \max_{e_\theta} \left\{p\left(\theta \mid e_\theta\right) X_\theta - \left(1 - p\left(\theta \mid e_\theta\right)\right) \xi_\theta + \left(U_\theta - c - e_\theta \psi_\theta\right)\right\},\, \theta \in \{u, r\} \tag{3}$$

Second, the optimal menu of contracts must satisfy the following incentive compatibility (IC) constraints that ensure that the θ-type supplier self-selects the contract designed for him, that is,

$$\pi_S^\theta\left(U_\theta, X_\theta, \xi_\theta \mid e_\theta^*\right) \geq \pi_S^\theta\left(U_{\check{\theta}}, X_{\check{\theta}}, \xi_{\check{\theta}} \mid \tilde{e}_\theta\right),\, \theta, \check{\theta} \in \{u, r\}, \check{\theta} \neq \theta \tag{4}$$

where $\tilde{e}_\theta$ is the optimal effort for the θ-type supplier should he mimic the $\check{\theta}$-type supplier (off-equilibrium decision), that is,

$$\tilde{e}_\theta = \max_{e_\theta} \left\{p\left(\theta \mid e_\theta\right) X_{\check{\theta}} - \left(1 - p\left(\theta \mid e_\theta\right)\right) \xi_{\check{\theta}} + \left(U_{\check{\theta}} - c - e_\theta \psi_\theta\right)\right\},\, \theta, \check{\theta} \in \{u, r\} \tag{5}$$

The buyer's problem is then to find the optimal menu of contracts $(U_\theta, X_\theta, \xi_\theta)$ that satisfies all of the constraints (2-5):

$$\begin{aligned} \max_{(U_r, X_r, \xi_r), (U_u, X_u, \xi_u)} \quad & \nu \pi_B^r\left(U_r, X_r, \xi_r \mid e_r^*\right) + (1 - \nu)\, \pi_B^u\left(U_u, X_u, \xi_u \mid e_u^*\right) \\ \text{Subject to} \quad & \text{Constraints } (2-5) \end{aligned} \tag{6}$$

where $\pi_B^\theta\left(U_\theta, X_\theta, \xi_\theta \mid e_\theta^*\right)$ denotes the buyer's expected profit provided that the θ-type supplier accepts the contract $(U_\theta, X_\theta, \xi_\theta)$ and subsequently exerts action e_θ^* as characterized in Lemma 1, that is,

$$\pi_B^\theta\left(U_\theta, X_\theta, \xi_\theta \mid e_\theta^*\right) = p\left(\theta \mid e_\theta^*\right) b - \left[p\left(\theta \mid e_\theta^*\right) X_\theta - \left(1 - p\left(\theta \mid e_\theta^*\right)\right) \xi_\theta + U_\theta\right] \tag{7}$$

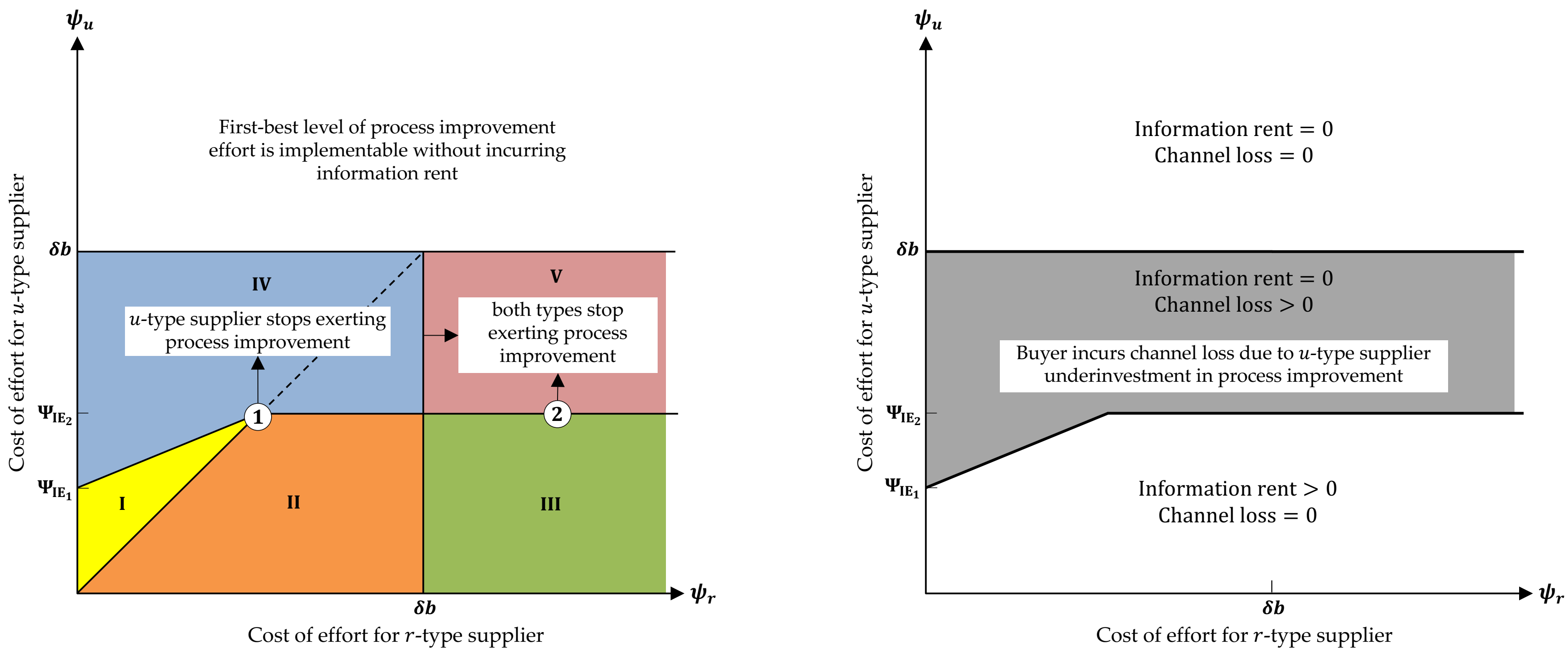
Note that the first term represents the buyer's expected revenue and the last three terms represent the net payment transferred between the buyer and the θ-type supplier. Recall that, under symmetric information, the θ-type supplier exerts the first-best effort level (denoted by e_θ^{fb}), and the buyer earns the entire channel profit. However, it can be easily verified that the same menu of contracts that induces e_θ^{fb} under symmetric information is not incentive-compatible for the r-type (more reliable) supplier under asymmetric information. The buyer then has two options: she needs to either modify the contract terms to make it incentive-compatible for the r-type supplier or induce the second-best level of effort (denoted by e_θ^*) on the u-type supplier. Each option comes at a cost to the buyer. Specifically, as we will discuss the details later, the r-type supplier, who is inherently more reliable, has incentives to mimic the u-type supplier by selecting the contract designed for him. To avoid such an opportunistic behaviour the buyer needs to pay for the r-type supplier's proprietary information through the contract terms designed for him. This results in the former inefficiency, which is called *information rent*. As we will show later, the amount of information rent is an increasing function of u-type supplier's cost of process improvement. Therefore, the buyer may find it better to stop inducing process improvement effort on the u-type supplier, resulting in the latter inefficiency called *channel loss*. Using the theory of mechanism design, one can reformulate the buyer's optimization problem as the weighted average of information rent and channel loss, with the weights represented by *a priori* beliefs. We delegate the detailed analysis to the Appendix and provide the complete equilibrium characterization of the optimal IE contract under asymmetric information in the following proposition.

PROPOSITION 2. *The second-best effort level e^*_θ and corresponding optimal IE contract $(U^*_\theta, X^*_\theta, \xi^*_\theta)$ are fully characterized in Table 5. Furthermore, it provides closed-form expressions for the information rent and channel loss incurred by the buyer under each case.*

As shown in Lemma 1, the buyer must provide the right amount of incentives to each supplier type to induce the process improvement under asymmetric information. Additionally, this proposition shows that these effort-inducing incentives should also be self-selected by the right supplier types to prevent them from choosing each other's contract. To summarize, in addition to the effort-inducing incentives, the buyer must also provide further incentives (called information rent). Luckily, it can be shown that information rent needs to be paid to only one of the supplier types. Given the ranking previously implied between supplier types (i.e., $\rho_r \geq \rho_u$, and $\varphi_r \geq \varphi_u$), in our model, it is always the r-type supplier who earns this information rent in equilibrium.

Table 5 Optimal contract, supplier's choice of action, information rent, and channel loss under IE contract

Region	Optimal menu of contracts $(U_r^*, X_r^*, \xi_r^*); (U_u^*, X_u^*, \xi_u^*)$	supplier's second-best effort	r-type supplier's off-equilibrium effort	Information rent	Channel loss
I	$\begin{cases} U_r^* &= c+\psi_r \\ X_r^* &= \frac{1-\varphi_u}{\delta}\psi_u - \psi_r \\ \xi_r^* &= \frac{\varphi_u}{\delta}\psi_u + \psi_r \end{cases}; \begin{cases} U_u^* &= c+\psi_u \\ X_u^* &= \frac{1-\rho_u}{\delta}\psi_u \\ \xi_u^* &= \frac{\rho_u}{\delta}\psi_u \end{cases}$	$e_r^* = 1;\ e_u^* = 1$	$\tilde{e}_r = 1$	$(\psi_u - \psi_r) + (\rho_r - \rho_u)\,\frac{\psi_u}{\delta}$	0
II	$\begin{cases} U_r^* &= c+\psi_r \\ X_r^* &= \frac{1-\rho_r}{\delta}\psi_r + \frac{\rho_r-\rho_u}{\delta}\psi_u \\ \xi_r^* &= \frac{\rho_r}{\delta}\psi_r - \frac{\rho_r-\rho_u}{\delta}\psi_u \end{cases}; \begin{cases} U_u^* &= c+\psi_u \\ X_u^* &= \frac{1-\rho_u}{\delta}\psi_u \\ \xi_u^* &= \frac{\rho_u}{\delta}\psi_u \end{cases}$	$e_r^* = 1;\ e_u^* = 1$	$\tilde{e}_r = 0$	$\psi_u + (\varphi_r - \rho_u)\,\frac{\psi_u}{\delta}$	0
III	$U_r^* = c; X_r^* = \frac{1-\varphi_u}{\delta}\psi_u; \xi_r^* = \frac{\varphi_u}{\delta}\psi_u;$ $U_u^* = c+\psi_u; X_u^* = \frac{1-\rho_u}{\delta}\psi_u; \xi_u^* = \frac{\rho_u}{\delta}\psi_u$	$e_r^* = 0;\ e_u^* = 1$	$\tilde{e}_r = 0$	$\psi_u + (\varphi_r - \rho_u)\,\frac{\psi_u}{\delta}$	0
IV	$U_r^* = c+\psi_r; X_r^* = \frac{1-\rho_r}{\delta}\psi_r; \xi_r^* = \frac{\rho_r}{\delta}\psi_r; U_u^* = c; X_u^* = 0; \xi_u^* = 0$	$e_r^* = 1;\ e_u^* = 0$	$\tilde{e}_r = 0$	0	$\delta b - \psi_u$
V	$U_r^* = U_u^* = c; X_r^* = X_u^* = 0; \xi_r^* = \xi_u^* = 0$	$e_r^* = 0;\ e_u^* = 0$	$\tilde{e}_r = 0$	0	$\delta b - \psi_u$



Notes. $\Psi_{IE_1} = \left[\frac{\delta(1-\nu)}{\delta(1-\nu)+\nu(\rho_r-\varphi_u)}\right]\delta b$; $\Psi_{IE_2} = \left[\frac{\delta(1-\nu)}{\delta(1-\nu)+\nu(\rho_r-\rho_u)}\right]\delta b$; The buyer incurs the information rent and channel loss with probability ν and $1-\nu$, respectively.

We now discuss information rent for the r-type supplier as characterized in Proposition 2 (see Table 5) because this type plays a key role in §7 in understanding the value of an audit. First, note that the buyer needs to pay information rent to the r-type supplier only when the u-type supplier is induced to exert effort. This phenomenon occurs because, in equilibrium, only the r-type has incentives to deviate and, if he deviates, he does so to earn incentives provided by the buyer to induce the u-type supplier to exert effort. Therefore, to satisfy the IC constraint of the r-type supplier, the buyer must guarantee that the r-type supplier does not earn higher profits if he chooses the contract designed for the u-type supplier. In other words, the information rent paid to the r-type supplier must be exactly equal to the expected profit that he would earn if he chose the u-type supplier's contract, (U_u^*, X_u^*, ξ_u^*), and exerted the best effort under this contract, that is, $\tilde{e}_r = e_r^*(U_u^*, X_u^*, \xi_u^*)$:

$$\text{Information rent paid to } r\text{-type } = \underbrace{U_u^* - (c + \tilde{e}_r \psi_r)}_{\text{fixed-term}} + \underbrace{[p(r \mid \tilde{e}_r) - p(u \mid e_u^*)](X_u^* + \xi_u^*)}_{\text{incentive-fee term}} \tag{8}$$

Note that information rent paid to the r-type supplier has two terms. The first term is a *fixed-term*, which accounts for the upfront transfer payment that needs to be paid to the u-type supplier to satisfy his participation (IR) constraint. The second term is the *incentive fee*, which represents the volume of incentives that needs to be paid to the u-type supplier to induce him to exert process improvement effort. Furthermore, both terms are modified to account for the r-type supplier's effort decision $\tilde{e}_r$ when he deviates. Specifically, the fixed-term is reduced by the r-type supplier's cost incurred given his off-equilibrium decision, and the incentive-fee term is multiplied by the relative reliability of the r-type supplier on the off-equilibrium path over the u-type supplier (measured by the difference in the success probabilities between the u- and r-type suppliers). To summarize, higher fixed and incentive payments for the u-type supplier result in higher information rent. In contrast, a lower relative reliability of the r-type over the u-type and a higher cost of effort incurred by the r-type supplier on the off-equilibrium path results in lower information rent. We can further simplify equation (8) by using the fact that the buyer in equilibrium always offers a break-even contract term to the u-type that just satisfies his IR constraint (i.e., $U_u^* = c + \psi_u$) and induces him to exert process improvement effort (i.e., $X_u^* + \xi_u^* = \frac{\psi_u}{\delta}$ - see Lemma 1). Substituting these contract terms into this equation (8) leads to the following simplified expression for information rent:

$$\text{Information rent paid to } s\text{-type } = \underbrace{\psi_u - \tilde{e}_r \psi_r}_{\text{fixed-term}} + \underbrace{[p(r \mid \tilde{e}_r) - p(u \mid e_u^*)]\frac{\psi_u}{\delta}}_{\text{incentive-fee term}} \tag{9}$$

By analyzing the impact of system parameters on information rent, we can obtain the intuition behind why the optimal IE contract leads to channel inefficiency for (i) relatively higher values of ψ_u, and (ii) lower values of ψ_r (see Table 5).

- First, note that the information rent (equation 9) increases in ψ_u. This increase occurs because the u-type supplier with high values of ψ_u needs stronger incentives to exert process improvement effort, and the buyer must provide the same incentives to the r-type supplier to satisfy his IC constraint. This situation implies that when ψ_u becomes very high, the buyer stops inducing the u-type supplier to exert process improvement effort to reduce information rent for the r-type supplier.
- Note that the region in which the optimal IE contract leads to channel inefficiency depends on parameters other than ψ_u. This is because the information rent depends not only on the contract terms offered to the u-type supplier but also on the extent of the information asymmetry between the u- and r-type suppliers. Recall that the suppliers can differ from each other in two ways. The first way is caused by the difference between the process improvement costs (measured by $\psi_u - \psi_r$) and the second way is the degree of reliability $p(r|e) - p(u|e)$. Note that the cost asymmetry $\psi_u - \psi_r$ affects the fixed term, whereas the reliability asymmetry $p(r|e) - p(u|e)$ affects the incentive-fee term in the information rent. The former implies that a more cost-efficient r-type (i.e., a lower ψ_r) benefits more from the information rent received through the direct subsidy that the u-type receives from the buyer in the form of an upfront payment. In contrast, the latter implies that a more reliable r-type (i.e., a higher $p(r|e)$) benefits more from the information rent received through the indirect subsidy that the u-type receives from the buyer in the form of contingent payments. These two observations imply that the optimal IE contract more likely leads to channel inefficiencies as ψ_r decreases and ρ_r increases because the buyer reduces the information rent for the r-type supplier by not providing effort-inducing incentives to the u-type supplier.
- Finally, an increase in *a priori* beliefs for the more reliable supplier (i.e., ν) also affects the likelihood that an optimal IE contract creates channel inefficiency. This higher likelihood is the result of the buyer paying information rent only to the r-type supplier, the probability of which increases in ν. Therefore, *ceteris paribus*, the expected costs of channel loss and information rent decrease and increase, respectively, in ν.

6. Audited-Effort (AE) Contract

In the previous section, we show that the buyer's inability to observe the action taken by the supplier has significant impacts on both information rent and channel inefficiency. In this section, we consider an audit setting in which the buyer receives a perfect signal on the action chosen by the supplier by incurring audit cost $\mathscr{A} > 0$ and uses this signal to enforce a particular action profile. Note that it is a common practice for the buyer to obtain independent verification of the supplier's action to use a (costly) audit (Chow 1982, Taylor 2002, Pun and Heese 2014). Let (e_r^*, e_u^*) denote the optimal action profile that the buyer wants to induce on her supplier. Note that even though the buyer can verify the supplier's effort, she cannot observe his type and, hence, does not verify whether the supplier's effort decision is optimal. Therefore, the optimal contract design boils down to an adverse selection problem with the following IR and IC constraints to ensure participation, that is,

$$\pi_S^{\theta}\left(U_\theta, X_\theta, \xi_\theta \mid e_\theta^*\right) = p\left(\theta \mid e_\theta^*\right) X_\theta - \left(1 - p\left(\theta \mid e_\theta^*\right)\right)\xi_\theta + \left(U_\theta - c - e_\theta^*\psi_\theta\right) \geq 0,\, \theta \in \{u, r\} \tag{10}$$

and self-selection, respectively:

$$\pi_S^{\theta}\left(U_\theta, X_\theta, \xi_\theta \mid e_\theta^*\right) \geq \pi_S^{\theta}\left(U_{\check{\theta}}, X_{\check{\theta}}, \xi_{\check{\theta}} \mid e_{\check{\theta}}^*\right), \tag{11}$$

where $\check{\theta} \neq \theta$. Finally, the optimal AE contract must maximize the buyer's payoff subject to the constraints (10) and (11):

$$\max_{(U_r, X_r, \xi_r), (U_u, X_u, \xi_u)} \nu \pi_B^r\left(U_r, X_r, \xi_r \mid e_r^*\right) + (1 - \nu)\, \pi_B^u\left(U_u, X_u, \xi_u \mid e_u^*\right) - \mathscr{A} \tag{12}$$

Note that observing the action profile modifies the optimal contract problem. Thanks to the audit, a deviating θ-type supplier has to choose not only the contract designed for the $\check{\theta}$-type supplier but also the effort induced for him, that is, $e_{\check{\theta}}^*$, where $\check{\theta} \neq \theta$ (see constraint (11)). This setting contrasts with the IE setting in which a θ-type supplier can deviate by choosing the contract designed for the $\check{\theta}$-type supplier and then continuing to exert the best effort under the deviated contract according to constraint (5). As it is shown in the following proposition, this setting would make deviation under the AE contract more costly for the θ-type supplier, which in turn enables the buyer to reduce distortions caused by asymmetric information.

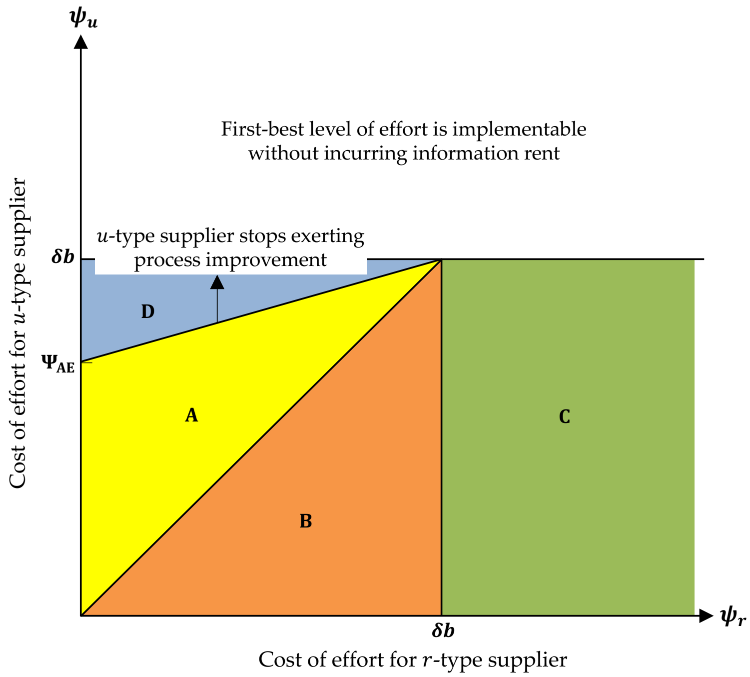
Proposition 3. *The optimal AE contract* $(U_\theta^*, X_\theta^*, \xi_\theta^*)$ *and the effort levels* (e_θ^*) *induced in equilibrium, as well as the decomposition of the total agency costs into information rent and channel loss, are characterized in Table 6.*

First, note from table 6 that under the AE contract, the buyer still needs effort-inducing incentive fees (i.e., non-zero reward and rebate terms) at least for one of the supplier types because even if she can verify the supplier's effort, she cannot observe his type. For example, consider Region A in table 6. If the buyer does not provide effort-inducing incentives for the r-type supplier, he can simply pretend to be the u-type to obtain a higher fixed-term payment offered to the u-type because $\psi_u \geq \psi_r$ in Region A. Similarly, in Region B, the buyer uses effort-inducing incentives to prevent the u-type from pretending to be the r-type. That said, a closer examination of information rent and channel loss expressions, as characterized in table 6, reveals that an audit can significantly reduce the agency costs associated with hidden information. As a result, the buyer can induce the first-best level of effort on the supplier in a less costly fashion. To explain the intuition behind this result, we need to revisit the information rent expression characterized in the previous section. Similar to an IE contract, the information rent under an optimal AE contract can be divided into two terms:

$$\text{Information rent paid to } s\text{-type } = \underbrace{U_u^* - \left(c + e_u^*\psi_r\right)}_{\text{fixed-term}} + \underbrace{\left[p\left(r \mid e_u^*\right) - p\left(u \mid e_u^*\right)\right]\left(X_u^* + \xi_u^*\right)}_{\text{incentive-fee term}} \tag{13}$$

Table 6 Optimal contract, supplier's second-best level of effort, information rent, and channel loss under AE contract

Region	Optimal menu of contracts $(U_r^*, X_r^*, \xi_r^*)\,;(U_u^*, X_u^*, \xi_u^*)$	supplier's second-best effort	Information rent	Channel loss
A	$U_r^* = c + \psi_r, X_r^* = \frac{\psi_u - \psi_r}{\rho_r}, \xi_r^* = 0;\ U_u^* = c + \psi_u, X_u^* = 0, \xi_u^* = 0$	$e_r^* = 1;\ e_u^* = 1$	$\psi_u - \psi_r$	0
B	$U_r^* = c + \psi_r, X_r^* = \frac{1-\rho_r}{\rho_r - \rho_u}(\psi_r - \psi_u), \xi_r^* = \frac{\rho_r}{\rho_r - \rho_u}(\psi_r - \psi_u);$ $U_u^* = c + \psi_u, X_u^* = 0, \xi_u^* = 0$	$e_r^* = 1;\ e_u^* = 1$	0	0
C	$U_r^* = c, X_r^* = 0, \xi_r^* = 0;\ U_u^* = c + \psi_u, X_u^* = 0, \xi_u^* = 0$	$e_r^* = 0;\ e_u^* = 1$	0	0
D	$U_r^* = c + \psi_r, X_r^* = 0, \xi_r^* = 0;\ U_u^* = c, X_u^* = 0, \xi_u^* = 0$	$e_r^* = 1;\ e_u^* = 0$	0	$\delta b - \psi_u$



Notes. $\Psi_{AE} = (1-\nu)\delta b$; The buyer incurs information rent and channel loss with probability ν and $1-\nu$, respectively.

We can further simplify this expression for information rent. Recall that under an optimal IE contract, the buyer needs effort-inducing incentives for both supplier types, whereas an audit eliminates its necessity for the u-type supplier. That is, $X_u^* + \xi_u^* = 0$ under AE, which removes the contribution of the "incentive-fee" term to the information rent, that is,

$$\text{Information rent paid to } r\text{-type } = \underbrace{\psi_u - e_u^* \psi_r}_{\text{fixed-term}} \tag{14}$$

In addition, the audit provides a second benefit to the buyer, namely, the buyer can employ an audited action profile (e_r^*, e_u^*) as a screening device to distinguish the r-type from the u-type. For example, consider Regions B and C in table 6. Note that as opposed to the IE setting, the r-type supplier is not free to exert any effort when he deviates. In fact, under the AE contract, the r-type supplier must choose $\tilde{e}_r = e_u^* = 1$ if he deviates, which in turn makes his deviation unprofitable because $\psi_r \geq \psi_u$ in both Regions B and C.

Finally, our last observation from table 6 is that, even though the AE contract helps eliminate agency costs for Regions B and C, it does not entirely eradicate them in Regions A and D. The reason comes from the trade-off between information rent and channel efficiency. On the one hand, in Region A, inducing a process improvement effort on both suppliers helps the buyer increase the total channel surplus. However, as previously explained, it requires her to pay information rent to the r-type supplier. On the other hand, by inducing the suppliers to exert different actions, the buyer can eliminate the information rent because she can use an audit as a perfect screening device to separate the r-type from the u-type supplier. However, as shown in Region D, this separation causes channel inefficiency.

In the next section, we compare optimal IE and AE contracts from the perspectives of the buyer, as well as the supplier and the entire channel. This comparison enables us to address the main research question of this paper, namely, what is the value of audit under information asymmetry for the buyer, the supplier and the total supply chain?

7. The Value of Audit

We analyze the value of an audit (VOA) from the perspectives of the buyer, the supplier, and the entire channel. First, note that the comparison of channel loss expressions characterized in propositions 2 and 3 for optimal IE and AE contracts, respectively, imply that the audit is always valuable from the channel perspective. However, to determine the value of an audit for both buyer and supplier, we need to take into account both information rent and channel loss under optimal IE and AE contracts:

Proposition 4. *The value of the audit for the buyer, supplier, and entire channel is characterized in Table 7. Furthermore, the value of the audit from the buyer's perspective also indicates an upper bound on the audit cost $\mathscr{A}$ should the AE be the optimal contract.*

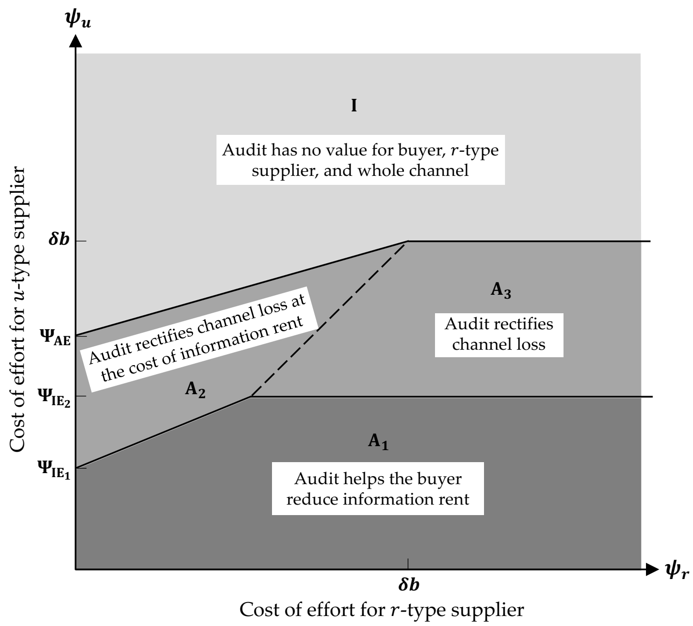
Note that the VOA characterized in Table 7 indicates only the difference between agency costs under IE and AE contracts; however, by employing the AE contract, the buyer incurs the cost of an audit $\mathscr{A} \geq 0$. Therefore, the AE contract is the superior contractual strategy for the buyer in Regions A_1, A_2, and A_3 as long as the VOA is greater than $\mathscr{A}$. In other words, the VOA from the buyer's perspective in Table 7 indicates an upper bound on the cost of an audit $\mathscr{A}$ whenever AE dominates IE (Regions A_1, A_2, and A_3). In what follows, we discuss how and when the audit has an actual effect on individual and channel profits. First, we start with the buyer.

VOA for the buyer: As shown in Table 7, an audit has a strictly positive effect on the buyer's payoff by eliminating either information rent (in Region A_1) or channel inefficiency (in Regions A_2, and A_3) incurred under an optimal IE contract. Even though the type of agency costs rectified by the audit is different, the value of the audit is ultimately driven by two factors.

- **[Efficiency-improving effect:]** On the one hand, fixed-term contracts are theoretically the best in terms of achieving channel efficiency but work only under a symmetric information scenario (see

Table 7 Value of Audit (VOA)

Region	buyer	r-type supplier	Channel
A_1	$\nu\left(\frac{\rho_r-\rho_u}{\delta}\right)\psi_u$	$-\nu\left(\frac{\rho_r-\rho_u}{\delta}\right)\psi_u$	0
A_2	$(1-\nu)\left[\delta b-\psi_u\right]-\nu\left(\psi_u-\psi_r\right)$	$\nu\left(\psi_u-\psi_r\right)$	$(1-\nu)\left[\delta b-\psi_u\right]$
A_3	$(1-\nu)\left[\delta b-\psi_u\right]$	0	$(1-\nu)\left[\delta b-\psi_u\right]$
I	0	0	0



Notes. The name of the region indicates the superior contracting strategy from the buyer's perspective, that is, "I" indicates that the IE contract is better than the AE contract, and "A_i" indicates that the AE contract is better than the IE contract. The expressions for Ψ_{IE_1} and Ψ_{IE_2} are characterized in Proposition 2, and Ψ_{AE} in Proposition 3.

Proposition 1). On the other hand, under a hidden information and action scenario, the buyer needs to offer incentive fees to both supplier types to induce them to exert process improvement efforts (see Proposition 2). An audit helps the buyer restore channel efficiency by customizing the contractual form based on the type of supplier, in the sense that—with the help of an audit—the buyer can offer the fixed-term contract to less reliable suppliers and use fixed-term incentive fees for more reliable suppliers (see Proposition 3).

• [**Screening effect:**] Given the linkage between the supplier's type and his effort, observing the latter provides the buyer with valuable information about the former. This situation implies that an audit can be used as an additional screening device by the buyer to separate more reliable suppliers from less reliable ones. In turn, doing so helps the buyer reduce the information rent incurred under an optimal IE contract.

VOA for the supplier: Depending on whether the audit has an efficiency-improving or screening effect, its value for the supplier can be positive or negative. First, consider Region A_1. As subsequently discussed, the audit is used in this region primarily as a screening device by the buyer and enables her to reduce the information rent, which then hurts the r-type supplier. In contrast, in Regions A_2 and A_3, an audit increases channel efficiency. Consequently, depending on whether or not the buyer shares some of the channel surplus with the r-type supplier through the information rent (see Regions A_2 and A_3), the audit either increases the r-type supplier's profit or keeps it unchanged.

VOA for the entire channel: Finally, when the audit has a screening effect, it does not have any actual value on the channel's surplus (see Region A_1). In other words, the audit simply transfers some of the surplus from the supplier to the buyer without changing the channel value. In contrast, when the audit has an efficiency-improving effect (i.e., in Regions A_2 and A_3), it indeed allows the entire channel to achieve its first-best efficiency (realized under a symmetric information scenario).

In the next section, we analyze the impact of system parameters on the value of an audit.

7.1. Impact of System Parameters on Value of Audit

Note that both the magnitude of the VOA and the size of Regions A_1, A_2, and A_3 (see Table 7) are affected by changes in the problem parameters. In this section, we focus on the sensitivity of the VOA to cost parameters ψ_u and ψ_r, unit revenue b, the impact of process improvement effort on the degree of reliability measured by δ, and the distribution of risks faced by different types of suppliers as measured by ν, ρ_θ, and φ_θ. We then use this analysis to identify the conditions under which the audit is beneficial to the individual parties as well as to the entire channel. The following proposition shows the impact of the system parameters on the VOA.

Proposition 5. *The impact of system parameters on the VOA for the buyer, supplier, and the entire channel is fully characterized in Table 8.*

Table 8 Impact of system parameters on VOA

VOA (A_1, A_2, A_3)	ψ_u	ψ_r	b	δ	ρ_r and φ_r	ρ_u and φ_u	ν
buyer	$(+,-,-)$	$(0,+,0)$	$(0,+,+)$	$(0,+,+)$	$(+,0,0)$	$(-,0,0)$	$(+,-,-)$
r-type supplier	$(-,+,0)$	$(0,-,0)$	$(0,0,0)$	$(0,0,0)$	$(-,0,0)$	$(+,0,0)$	$(-,+,0)$
Channel	$(0,-,-)$	$(0,0,0)$	$(0,+,+)$	$(0,+,+)$	$(0,0,0)$	$(0,0,0)$	$(0,-,-)$

Notes. The profile $(\cdot,\cdot,\cdot)$ indicates the impact of system parameters on the VOA in Regions A_1, A_2, and A_3, respectively. "+", "-", and "0" indicate that the increase in the system parameter has an increasing effect, decreasing effect, and no effect on the VOA, respectively.

Considering Table 8, we can analyze the impact of the parameters on the VOA for the buyer depending on whether they affect an audit's role in reducing channel loss (i.e., *efficiency-improving effect*) or information rent (i.e., *screening effect*). Then, we consider the impact of the parameters on the VOA for the supplier and the entire channel.

Impact of ψ_u and ψ_r: First, note from Table 7 that the VOA for the buyer is non-monotone in ψ_u. The VOA first increases in ψ_u in Region A_1 and decreases in Regions A_2 and A_3. The intuition is as follows. Recall that higher values of ψ_u increase the information rent and reduce the channel loss incurred under an optimal IE contract. Therefore, higher values of ψ_u amplify the screening effect (which increases the VOA for the buyer in Region A_1) and dampen the efficiency-improving effect of an audit (which decreases the VOA for the buyer in Regions A_2 and A_3). Additionally, recall that higher values of ψ_r decrease the information rent transfer between buyer and supplier. Therefore, in Region A_2, where the buyer shares a portion of the channel surplus with the supplier in the form of an information rent transfer under the optimal AE contract, she shares less as ψ_r increases, which in turn increases the VOA for the buyer.

Impact of b and δ: Both b and δ increase the channel profit, which amplifies the efficiency-improving effect of an audit for the buyer. Therefore, the VOA for the buyer increases in both b and δ in Regions A_2 and A_3. In contrast, the trade-off between channel efficiency and information rent suggests that, for higher values of b and δ, incurring a channel loss would become more expensive for the buyer relative to incurring information rent. Therefore, higher values of b and δ dampen the screening effect of an audit (and decrease the VOA for the buyer) in Region A_1.

Impact of ν: Note that ν affects only the relative weight of the channel loss and information rent for the buyer because ν and $1-\nu$ measure the likelihoods that the supplier is the r-type (when the buyer incurs the information rent) and the u-type (when the buyer incurs a channel loss), respectively. Because higher values of ν increase the relative importance of the information rent, an increase in ν amplifies the screening effect (which increases the VOA for the buyer in Region A_1) and dampens the efficiency-improving effect (which decreases the VOA for the buyer in Regions A_2 and A_3).

Impact of ρ_θ and φ_θ: Note that both $\rho_r - \rho_u$ and $\varphi_r - \varphi_u$ measure the degree of information asymmetry between the buyer and the supplier, which determines the amount of the information rent that transfers between them. Therefore, lower values of ρ_r and φ_r and higher values of ρ_u and φ_u dampen the screening effect of the audit, which decreases the VOA for the buyer in Region A_1. Regarding the impact on the efficiency-improving effect of the audit, we need to consider how Regions A_2 and A_3 change in ρ_θ and φ_θ because, in these regions, the VOA expressions for the buyer depend on neither of them (see Table 7). The analysis of Ψ_{IE_1} and Ψ_{IE_2} reveals that the former converges to Ψ_{AE} and the latter to δb (implying that both A_2 and A_3 vanish) as $\rho_r - \rho_u$ and $\varphi_r - \varphi_u$ go to zero. In turn, as shown in the following proposition, this analysis implies that not only the VOA for the buyer but also those for the supplier and the entire channel vanish as $\rho_r - \rho_u$ and $\varphi_r - \varphi_u$ go to zero:

Proposition 6. *The VOA goes to zero for the buyer, the supplier, and the entire channel as $\rho_r - \rho_u \to 0$ and $\varphi_r - \varphi_u \to 0$.*

As we discussed in §1, different from our results, Laffont and Martimort (2002) show that auditing the agent's actions has no value for the principal under a standard mixed model (i.e., when the agent is risk neutral and not protected by limited liability constraints) in which it is assumed that the impact of the agent's action on the likelihood of $q_\theta = 1$ is the same for both $\theta = r$ and $\theta = u$ (i.e., in terms of our notation, they assume that $\rho_r = \rho_u$ and $\varphi_r = \varphi_u$). This proposition shows that our results coincide with Laffont and Martimort (2002) in the limit when the difference between the survival probabilities for r- and u-type suppliers for the same level of effort goes to zero.

Up to this point in this section, we only focus on the impact of the parameters on the VOA for the buyer (i.e., the first row in Table 8). However, by using the relationship between VOAs for the buyer, the supplier, and the entire channel under efficiency-improving and screening effects of the audit, we can easily extend this discussion to the impact of parameters on VOAs for the supplier and the entire channel (i.e., the second and third rows in Table 8, respectively). Note that when the audit's role is to reduce the information rent, the VOAs for the buyer and the supplier move in opposite directions. This situation implies that all of the parameters that increase the VOA for the buyer in Region A_1 decrease the VOA for the supplier and do not affect the VOA for the entire channel in the same region. These changes occur because the audit redistributes the surplus from the supplier to the buyer without changing the entire channel value. In contrast, when the audit's role is to increase channel efficiency, a change in the value of a parameter that causes an increase in the VOA for the buyer always causes an increase in the VOA for the channel. However, depending on whether the resulting surplus is shared with the supplier (in Region A_2) or not (in Region A_3), an increase in the VOA for the buyer either causes an increase in the VOA for the supplier or keeps it unchanged.

8. Conclusions

In this paper, we explore the value of audit for a supply chain where a buyer has to contract with a supplier whose true state of delivery reliability and actions are not observable. We analyzed two contractual mechanisms for the buyer to interact with such suppliers. In the first mechanism, the buyer offers to the supplier a menu of contracts both to screen his reliability and to induce him to exert a process improvement effort (henceforth called Induced-Effort (IE) contract). In the second one, in addition to offering a menu of contracts, the buyer also audits the supplier's effort (henceforth called Audited-Effort (AE) contract).

The characterization and comparison of optimal contracts under two mechanisms yield insights regarding the impact of audit on equilibrium decisions and payoffs of individual supply chain parties as well as total supply chain. In terms of the impact on equilibrium decisions, we find that the audit enables the buyer to customize her contract offering based on the reliability type of the supplier. Namely, the optimal menu of contracts under AE consists of a fixed-price contract for a low-reliable supplier and a fixed-price-incentive-fees for a high-reliable one. In comparison with the optimal menu of contracts under IE, which consists of fixed-price-incentive-fees for both supplier types, AE has two effects: (i) efficiency-improving effect, and (ii) screening effect. First one is related to the restoration of channel efficiency caused by removal of effort-inducing incentives from the low-reliable-type's contract offering and replacing them with audited effort. Second one is related to the exploitation of linkage between supplier's reliability and his effort via audit. In other words, by observing supplier's effort, the buyer can screen more reliable supplier from less reliable one.

The analysis of the value of audit from each supply chain party's perspective reveals that the first effect of the audit may benefit both the buyer and supplier due to an increase in supply-chain efficiency, whereas the second effect benefits the buyer and hurts the supplier. Finally, the sensitivity analysis with respect to system parameters help us understand when audit is beneficial (resp., when it is not) for the buyer, the supplier and total supply chain.

The above-mentioned results shed some managerial insights into the role of auditing for different supply chains. Consider an original equipment manufacturer, like Toyota, whose supply base mostly consists of local suppliers. In such cases, the degree of information asymmetry between the manufacturer and its suppliers would be relatively mild. Hence, the manufacturer mainly enjoys the efficiency-improving effect of audit to rectify channel loss. Note that in this case, audit may be of interest to the suppliers as well especially when the resulting increase in the efficiency of channel is shared between the channel parties. On the other hand, in the cases of companies that extensively use global sourcing (such as Apple), they would benefit from screening-effect of the audit to reduce the information rent transfers. Finally, the companies that do not have prior experience with their suppliers around the globe can also enjoy the screening effect of audits and use it to increase the overall end-to-end visibility of their supply chains.

The model presented in this paper can be extended in multiple directions. In this paper, we focus on the supply chain setting between a risky supplier (agent) and a buyer (principal). However, we can show that both the methodology and results of this paper can be applied to a sales relation between a manufacturer (principal) and a retailer (agent) in which the retailer has private information regarding the true demand state and the hidden actions of the retailer affect the demand state. Based on the results derived in this paper, we can fully characterize when auditing hidden actions of the retailer generates non-zero benefit for the manufacturer, retailer as well as the total distribution channel.

We also discuss the implications of relaxing some of the assumptions made in this paper. We assume that supply chain firms obtain a perfect signal by auditing the actions of their partners. One possibility is to introduce noise into the audit. We expect that this extension would dilute the screening effect of the auditing, which may increase the information rent paid under the AE contract. Hence, under the noisy-audit scenario, AE may loose some of its appeal against IE. Another possibility is to consider a probabilistic audit scenario. Even though we did not conduct a full analysis, our preliminary works suggest that by randomizing between audit and no-audit scenarios, indeed, the buyer can save some of the auditing cost and at the same time enjoy the two benefits explained above. Last but not least, we believe that audit has become an increasingly important issue for many companies as they expand their supply bases locally and globally. We hope that our model will contribute to understanding the key factors of this issue.

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