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Probabilistic Audit in a Revenue Sharing Contract Under Asymmetric Demand Information

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Abstract
A two-echelon supply chain comprising a supplier and a retailer, coordinated by a revenue-sharing contract has been studied. The supplier knows the realized demand only from a sales report submitted by the retailer at the end of each decision period. Possession of private information about the market demand allows the retailer to under-report sales. To protect revenue loss from this under-reporting, the supplier uses audit probabilistically to check the retailer's dishonesty. Unlike designing a mechanism for the supplier to elicit private information from the retailer, which has been predominantly discussed in the literature, this study proposes a policy where the players can improve their expected profit compared to what they would have earned when the retailer had to reveal truthful information. Our study finds that the supplier benefits from the retailer's dishonesty, provided dishonesty is limited with the help of a probabilistic audit process. Both players' expected profits are higher in our proposed policy than what they would earn under a truth-inducing policy. These findings suggest that future studies focus on achieving social welfare instead of concentrating only on truth-inducing mechanisms. A numerical analysis of the optimization problem is performed to find the optimal audit probability. Our results will help a manager in a supplying firm design a revenue-sharing contract when she cannot observe her retailer's revenue without an audit.

Keywords- Supply chain contracts, Principal-agent problem, Dishonest retailer, Revenue-sharing contract, Probabilistic audit.

1. Introduction

A supply chain is greatly affected by the problem of double marginalization. Revenue-sharing (Cachon and Lariviere, 2001) is a contract type to reduce this problem and is prevalent in the retail sector (Crittenden et al., 2009). However, this contract is not self-enforcing (Schwartz and Scott, 2003) because a retailer benefits by understating the actual sales figure since he (we refer to the supplier as 'she' and the retailer as 'he' in this article) can transfer less than the contracted revenue share to his supplier (Cachon and Lariviere, 2001). Possession of private information in the supply chain about the demand gives him the scope to under-report sales revenue (Venkataraman and Asfaw, 2019). Yang et al. (2018) has investigated such a supply chain with the objective of coordinating it.

This under-reporting of sales creates conflicts in a supply chain since the supplier is deprived of her rightful share of revenue (Goldstein, 2015). Real estate franchisor Century 21 filed a lawsuit against one of its franchisees, CLTM, for not paying the rightful franchise fee (Goldstein, 2015). Studios sued chains like Blockbuster and Hollywood Video for under-reporting revenue (James, 2013). The supplier must adopt means to prevent revenue loss from under-reporting sales. Contract mechanisms are designed to mitigate this problem of under-reporting.

Two broad approaches to study the above problem in the literature are (i) mechanism design to elicit private information from the retailer and (ii) punitive measures to discourage the retailer from under-reporting. A few notable studies with the first approach are: addressing the problem of inflating the demand forecast by an agent in a two-stage supply chain (Cachon and Lariviere, 2001), inserting a return policy within the revenue-sharing framework (Arya and Mittendorf, 2004), designing a menu of contracts where the customer returns rate is retailer's private information (Huang and Yang, 2015), designing a menu of contracts in case of selling virtual products (Avinadav et al. 2021). However, Bhattacharyya et al. (2020) proved that a two-staged supply chain could not be coordinated by a menu of revenue-sharing contracts when the demand state is high. Chernonog (2021) designs an incentive mechanism for a two-echelon supply chain where a manufacturer has private information and interacts via a consignment contract with revenue sharing. The study finds the condition for information sharing beyond which social welfare is not possible. In the second approach, which is an adoption from the tax evasion literature, the supplier can audit the sales reports and penalize the retailer if there is any revenue understating. The supplier can audit every sales report to stop this under-reporting completely. However, the audit cost makes her adopt a probabilistic audit (Townsend, 1979), which involves auditing only a random sample of the reports.

We use the problem settings from Bhattacharyya et al. (2020) and intend to find an optimal audit policy for the supplier in a two-stage supply chain where demand is visible only to the retailer. We aim to maximize the supplier's expected revenue instead of strictly eliciting the retailer's private information. We compare our prescribed policy with a truth-inducing one and show the conditions under which the supplier is better off compared to the second one. We address the following two research questions:

Q1. Can profit maximization be an objective for the supplier using a probabilistic audit instead of eliciting truthful information from the retailer in a two-stage supply chain with a two-part demand distribution under information asymmetry?
Q2. Whether social welfare is possible in the above scenario?

This paper has been organized as follows. In Section 2, we review the relevant literature to our problem. In Section 3, we model the problem and define the truth-inducing policy. Section 4 presents the results of the numerical simulations and proposes an algorithm to find the optimal policy. In Section 5, we summarize our findings and conclude the article.

2. Literature Review

In an audit-based contract, the supplier will call an audit if she suspects the retailer's actions. The players mutually decide on terms and conditions (such as audit frequency) before signing the contract. These conditions are explicitly documented in the contract itself. The contract penalizes the retailer if he is found cheating during an audit.

The probabilistic audit is modeled in contract design for a regulator where the agent reports its cost structure for a product (Baron and Besanko, 1984; Laffont and Tirole, 1986), enabling self-reporting of crimes by an individual (Kaplow and Shavell, 1994), the tax enforcement perspective where the taxpayers tend to under-report their income (Crocker and Slemrod, 2005; Sandmo, 2005). Baron and Besanko (1984) developed a single-period model where a regulator sets the unit retail price for a monopolist's product based on a report describing the cost structure of the product. The retailer has the motivation to overstate his cost while reporting to get a higher price for his product and the regulator's subsidy. In this case, an audit mechanism is designed to demotivate the agent from the overstating cost. Their study also proposes a revelation game for the monopolist to disclose truthful information. Laffont and Tirole (1986) recommend using accounting data by the manufacturer to regulate a supplier when the supplier has better information about the cost and makes an effort for cost reduction.

Two significant differences between a tax problem or a regulator's problem and ours are: (i) the tax problem starts after a taxpayer realizes his revenue. But the revenue sharing problem begins when a retailer places an order. (ii) Frequent auditing increases tax collection. But a high audit probability affects the retailer's order quantity and the supplier's wholesale revenue. Heese and Kemahlioglu-Ziya (2014) adopt the tax evasion modeling approach to the revenue under-reporting problem by a retailer to his supplier in a revenue-sharing contract. They propose a mechanism that can exploit a rational retailer's opportunistic behaviour to the supplier's benefit using an audit policy. They find profit-maximizing to be a better objective than the truth-inducing from the retailer. We differ from their problem in that our players have a different basis for demand forecast (Farlow et al., 1996).

This article investigates a two-stage supply chain under a revenue-sharing contract where the retailer has private information about demand. The supplier and the retailer have a different basis for their demand forecast. We seek to find a policy, if there exists one, that maximizes the expected profits of the players rather than eliciting the truth from the retailer. We compare this policy with a truth-inducing policy and show the conditions under which the supplier may benefit by not chasing the truth, and social welfare may also be realized.

3. Analytical Model

We develop our model on a Newsvendor Problem (NVP) framework. The sequence of events is: (i) players agree to a revenue-sharing contract that includes the audit clause, (ii) the retailer places his order for a certain quantity that maximizes his expected profit, (iii) the supplier allocates items to meet the retailer's demand, (iv) Demand in the market is revealed, and the retailer earns his revenue., (v) the retailer reports his sales revenue to the supplier, and the supplier takes her decision for auditing.

3.1 Problem Description

In a month, the retailer orders Q items which the supplier fulfils at a unit wholesale price w $(w > c)$ while her unit production cost is c $(c > 0)$. The retailer could sell A (= $min\,\{Q, D\}$ where D is the realized demand) items in the market at a unit price r $(r > w > c)$ (Qin and Yang, 2008) and shares α ($0 \leq \alpha \leq 100$) percent of r with the supplier. The retailer's salvage revenue from an unsold item, s $(s < c)$, and goodwill loss for an unmet demand, g $(g \geq 0)$, are not shared. He submits a report every month-end to his supplier indicating R as the sales figure that forms the basis for contracted revenue transfer. The supplier can call for an audit according to the pre-announced probability, and she will surely know the actual sales from it. The retailer must pay a penalty if he under-reports revenue and bears the audit cost (C_a). Otherwise, the audit cost is accrued to the supplier. The supplier has a history of sales reports wherein sales figures range in $[a, c]$ ($a \geq 0$, $c > 0$) and are common knowledge. She considers $[a, b]$ ($b > 0$) and $(b, c]$ to be the high (H) and low (L) demand respectively, referred hereafter as states. The respective order quantities are Q_L, Q_H while $f_L(x)$ (b $\geq$ x $\geq$ a) and $f_H(x)$ (b < x $\leq$ c) are the probability density functions (PDF). $F_L(x)$, $F_H(x)$ are the respective cumulative density functions (CDF). The proportion of low (high) demand reports in the history is p ($1-p$), and this is also the supplier's subjective probability of low (high) demand state (Heese and Kemahlioglu-Ziya, 2016). The retailer's demand estimate follows PDF $f(D)$ ($D \geq 0$) in a single bucket $[a, c]$. The supplier needs to decide the audit probability and the penalty function. The audit probability, $P(Q, R)$, is a function of Q and R while the penalty, *T(A,R)*, is a function of *A* and *R*. The retailer makes two decisions: (i) quantity to order and (ii) quantity to report (*R*). Since the players have different basis for their demand forecast, Q and R values will be different in their calculations. We denote Q_s, R_s to be the order quantity and reported quantity, respectively, in the supplier's calculation while the corresponding values in retailer's calculation are Q_r, R_r.

3.2 The Supplier's Problem

The supplier decides *P(Q, R)* and *T(A,R)* such that the retailer orders optimally. Since *A* is known to her only from an audit, she uses expected actual sales (A') given the probability of low demand state (*p)* calculated as Eq. (1), for her calculations.

$$A' = (1-p)\{(1-p)E_{H,H} + pE_{H,L}\} + p\{(1-p)E_{L,H} + pE_{L,L}\}$$
$$= (1-p)\left[(1-p)\int_b^Q xf_H(x)dx + \int_Q^c Qf_H(x)dx + p\int_a^b f_L(x)dx\right] + p[(1-p)\int_b^c Qf_H(x)dx + p\{\int_a^Q xf_L(x)dx + \int_Q^b Qf_L(x)dx\}] \quad (1)$$

Here, $E_{i,j}$ ($i, j \in \{L, H\}$) denotes the supplier's expected sales when the retailer orders Q_i($i\in\{L, H\}$) and realizes demand equal to Q_j ($j\in\{L,H\}$). We assume that a rational supplier won't initiate audit if the ordered quantity is Q_L due to (i) low expected revenue recovery which may not cover her audit cost, (ii) her belief that a rational retailer will not raise suspicion by reporting a low figure while the ordered quantity is itself low (Q_L). However, for Q_H, she will surely audit if $R < A'$ since she expects high revenue recovery. But $P(Q,R) < 1$ if $R > A'$ since she is not fully sure of under-reporting even though the expected recovery might be high. Payoff for the supplier (U^S) is calculated as in Eq. (2) that comprises a wholesale revenue corresponding to Q, a contracted revenue share against R and recovery amount from the audit.

$$U^s = \begin{cases} -cQ + wQ + \alpha rR & if\ Q \epsilon Q_L \\ -cQ + wQ + \alpha rR + P(Q,R)\{T(A,R) - C_a\} & if\ Q \epsilon Q_H, R \geq A' \\ -cQ + wQ + \alpha rR + T(A,R) - C_a & if\ Q \epsilon Q_H, R < A' \end{cases} \quad (2)$$

The supplier's expected profit (π^s) is given by Eq. (3) while Eq. (4) gives the retailer's expected profit in the supplier's calculation, Supplier's expected optimal order (Q_s^*) and reported quantity (R^*) from the retailer is given by Eq. (5) and Eq. (6), respectively. Individual Rationality constraint, Eq. (7), implies that the retailer will participate in the contract only if he gets a positive profit.

$$\pi^s = (w-c)Q + \alpha rR + P(Q,R)\{T(A',R) - C_a\} \quad (3)$$
$$\pi_s^R = (w-c)Q + rA' - \alpha rR - P(Q,R)T(A',R) \quad (4)$$
$$Q_s^* = \underset{Q}{\operatorname{argmax}}\, \pi_s^R\ ;\ given\ f_L(x), f_H(x) \quad (5)$$
$$R^* = \underset{R}{\operatorname{argmax}}\, \pi_s^R\ ;\ given\ Q \quad (6)$$
$$\pi_s^R(w, \alpha, P(Q,R), T(A',R)) > 0 \quad (7)$$
$$\max_{w,\alpha,P,T} \pi^s = (w-c)Q_s^* + \alpha rR^* + P(Q_s^*, R^*)\{T(A',R^*) - C_a\} \quad (8)$$

Substituting Q_s^*, R^* from (5) and (6) respectively into (3) gives the supplier's objective (8) subjected to the constraints (4), (5), (6), and (7).

3.3 The Retailer's Problem

The retailer decides order quantity Q_r^* that maximises his expected profit given *P(Q, R)* and *T(A, R)*. His payoff comprises of: (i) wholesale cost (*w*× *Q*), (ii) sales revenue (*r*×*min{D, Q}*), (iii) contracted revenue share to the supplier ($\alpha \times r \times R$), (iv) a penalty conditional on his reporting decision and supplier's auditing decision. He reports the actual sales (*A*) if he ordered Q_L. In case of Q_H he reports *R*. For *R*<*A*, he is penalized an amount *T(A, R)* if there is an audit. Otherwise, he enjoys an additional revenue (A-R)×α×r. His payoff, thus, is expressed in Eq. (9)

$$U^R = \begin{cases} -wQ + (1-\alpha)rR + [Q-A]^+s + [A-Q]^+g & if\ Q\ \epsilon\ Q_L \\ -wQ + (1-\alpha)rR + [Q-A]^+s + [A-Q]^+g & if\ Q\ \epsilon\ Q_H, R = A \\ -wQ + rA + [Q-A]^+s + [A-Q]^+g - \alpha rR - \delta T(A,R) & if\ Q\ \epsilon\ Q_H, R < A \end{cases} \quad (9)$$

$$max\, U^R = max\{U^R(Q^* \in Q_L),\ U^R(Q^* \in Q_H, R = A), U^R(Q^* \in Q_H, R < A)\} \quad (10)$$

where, δ is a binary variable that takes value one if R < A, otherwise zero. His objective is to select the option in U^R that maximises his payoff which is represented in Eq. (10). Since, the retailer reports A when he orders Q_L, we will focus only on the cases in Eq. (9) where he orders Q_H. We find that the retailer under-reports only if he gains more than reporting the truth. This is an obvious condition that validates our model. Retailer's expected profit (π_r^c) for a policy (Q_r, R_r) is given by Eq. (11). He decides his order quantity (Q_r^*) and reported quantity (R_r^*) that maximises Eq. (11) and these values are given by Eq. (12) and Eq. (13), respectively. We use backward induction to solve the retailer's problem given by Eq. (11), Eq. (12), and Eq. (13).

$$\pi_c^r = -wQ + \int_0^{Q_r}(rD - \alpha rR_r + s(Q_r - D) - P(D,R_r)T(D,R_r))f(D)dD + \int_{Q_r}^{\infty}(rQ_r - \alpha rR_r - g(D - Q_r) - P(Q_r,R_r)T(Q_r,R_r))f(D)dD \quad (11)$$

$$Q_r^* = \underset{Q}{\text{argmax}}\, \pi_c^r \ ;\ given\ P(Q_r,R_r)T(Q_r,R_r))f(D) \quad (12)$$

$$R_r^* = \underset{R}{\text{argmax}}\, \pi_c^r \ ;\ given\ Q_r, P(Q_r,R_r)T(Q_r,R_r))f(D) \quad (13)$$

Lemma 1: Equation 11 is concave only if:

(i) Marginal decrease of expected penalty in R_r for a value of Q_r is decreasing, i.e.

$$-\int_0^{Q_r}\frac{\partial^2}{\partial R_r^2}P(Q_r,R_r)T(D,R_r)f(D)dD - \int_{Q_r}^{\infty}\frac{\partial^2}{\partial R_r^2}P(Q_r,R_r)T(Q_r,R_r)f(D)dD < 0.$$

(ii) The marginal increase in penalty for a given value of R_r, is increasing in ordered quantity,

$$\frac{\partial^2}{\partial Q_r^2}\{P(Q_r,R_r)T(Q_r,R_r) \geq 0.$$

The above lemmas can be derived from the condition of concavity ($\frac{\partial^2\pi_c^r}{\partial Q_r^2} < 0$ and ($\frac{\partial^2\pi_c^r}{\partial R_r^2} < 0$) for the respective Hessian.

Proposition 1: At optimal reported quantity, total marginal decrease in penalty in Q_r equals the unit revenue shared by the retailer with the supplier. i.e.,

$$-\int_0^{Q_r}\frac{\partial}{\partial R_r}P(Q_r,R_r)T(D,R_r)f(D)dD - \int_{Q_r}^{\infty}\frac{\partial}{\partial R_r}P(Q_r,R_r)T(Q_r,R_r)f(D)dD = r\alpha \quad (14)$$

First Order Necessary Condition (FONC) of π_c^r gives Eq. (14). We derive the optimal reported quantity (R_r^*) given the ordered quantity from Eq. (13). This R_r^* is substituted in Eq. (12) that gives optimal order quantity, Q_r^* from FONC w.r.t. Q_r. These values are substituted in Eq. (14) to find the optimal objective function. Given the complexity of the above problem, we proceed to solve it numerically in section 4.

3.4 Truth Inducing Auditing Policy

The retailer always reports the actual sales, *A*, in this policy. We add a constraint *R* = *A* to the problem defined by Eq. (6), Eq. (7), Eq. (8). Hence, the problem reduces to a standard newsvendor problem as in Eq. (15) that gives the retailer's profit function ($\hat{\pi}_R$). The first order necessary condition gives his optimal order quantity in Eq. (16). The supplier's expected profit in this policy ($\hat{P}, \hat{T}$) under symmetric demand information is given by Eq. (16). We consider the results from this policy as the benchmark for our model.

$$\pi_c^r = -wQ + \int_0^Q \{(1-\alpha)rD + (Q-D)s\} f(D)dD + \int_Q^\infty \{(1-\alpha)rQ - (D-Q)g\} f(D)dD \tag{15}$$

$$\hat{Q} = F^{-1}\left(\frac{(1-\alpha)r - g - w}{(1-\alpha)r - g + s}\right) \tag{16}$$

$$\hat{\pi}_s = (w-c)\hat{Q} + \int_0^{\hat{Q}} \{\alpha rD - P(\hat{Q}, D)C_a\} f(D)dD + \int_{\hat{Q}}^\infty \{\alpha r\hat{Q} - P(\hat{Q}, \hat{Q})C_a\} f(D)dD \tag{17}$$

4. Numerical Experiment

This section aims to get insights from our model for a particular instance of audit probability and penalty functions and compare the results with those from the truth-inducing policy. We aim to find a few characteristics of an optimal policy for the players from our numerical experiments.

4.1 Experimental Set-up

We set the parameters like Bhattacharyya et al. (2020) as follows: unit production cost(*c*) to \$20, unit wholesale price (*w*) to \$30, unit retail price (*r*) to \$100, revenue-sharing fraction (*α*) to 20%, unit salvage value (*s*) to zero, unit goodwill loss (*g*) to zero, supplier's subjective probability (*p*) of low demand state to *0.5*. Sales figure history ranges uniformly in *[50,100]*. In supplier's consideration, low demand (*L*) and high demand (*H*) follow *Unif[50,70]* and *Unif(70,100]* respectively. An audit process costs (C_a) 100\$. We borrow the audit probability function, *P(Q, R) = γ(Q−R)/ Q ; γ > 0* and penalty function, *T(A,R) = 2(A −R)r* from Bhattacharyya et al. (2020). Here γ, denotes the supplier's weight to the mismatch between *Q* and *R*, referred hereafter as 'probability weight', which we use as a proxy to *P(Q, R)* in our numerical analysis.

4.2 Results and Discussions

When γ = 1, Q_s^* turned out to be larger than Q_r^* as shown in Figure 1(i). The retailer's expected profit is concave for $Q_s \in [21{,}183]$ and $Q_r > 15$ such that [21,183] is the common range where π_c^r is higher than $\hat{\pi}_R$ but it is lower than π_s^R. Therefore, a rational supplier will not offer this policy (γ = 1) since she cannot expect the retailer to report the truth here. Figure 1(ii) shows the situation when γ = 2. Both the players' expected profits are higher in this policy compared to the truth inducing policy, but the retailer's profit decreases from the previous policy (γ = 1). Figure 1(iii) shows the scenario when γ = 3. Retailer expects almost equal profit in this policy and the truth-inducing policy in the supplier's calculation. But the retailer is worse off in his calculation. On the other hand, the supplier is worse off from the truth-inducing policy. This is because of the combined effects of (i) retailer's reduced order quantity and (ii) reduced revenue recovery from increased truthfulness by the retailer while the audit cost surges. Thus, the supplier will not prefer this policy either.

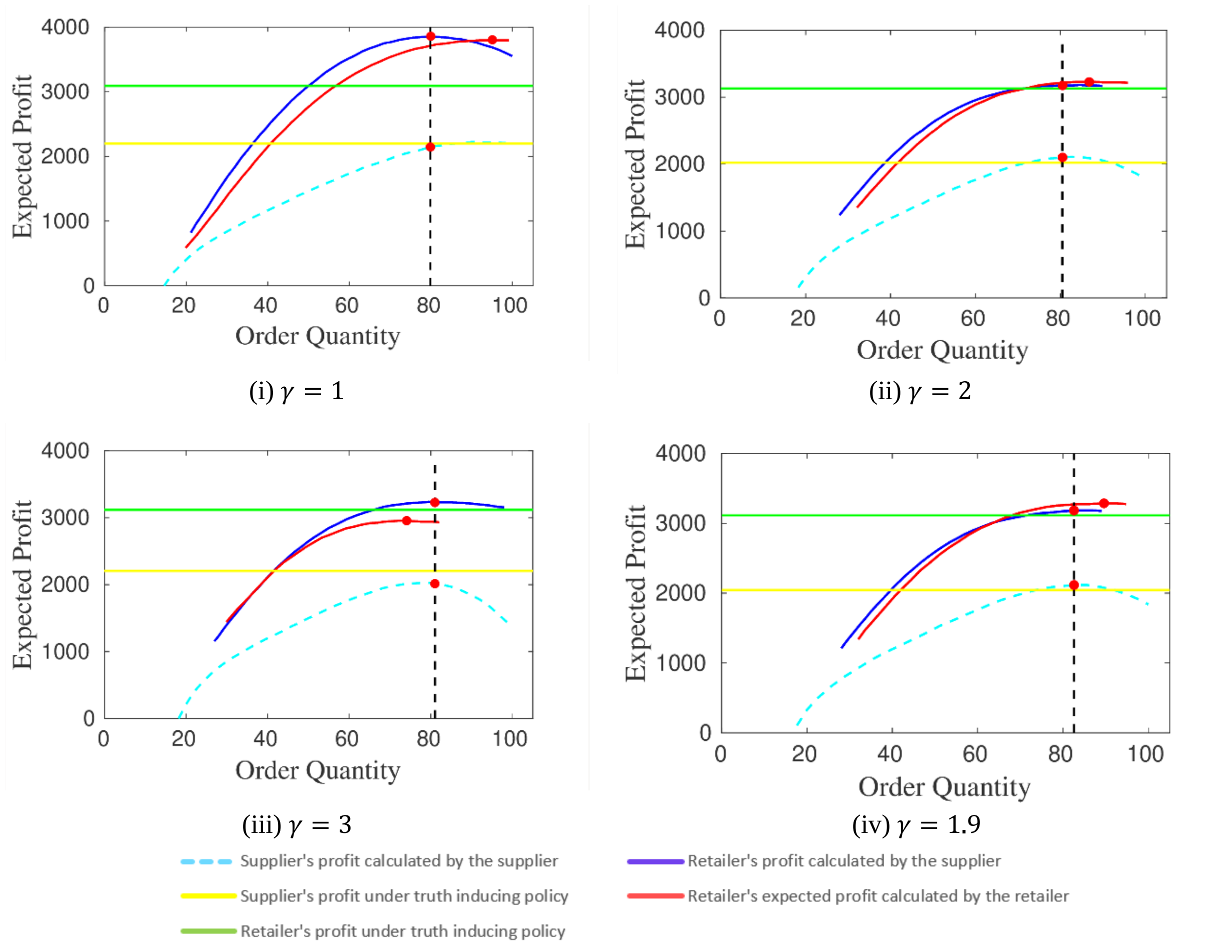

Figure 1. The supplier's and the retailer's expected profit for different probability weights.

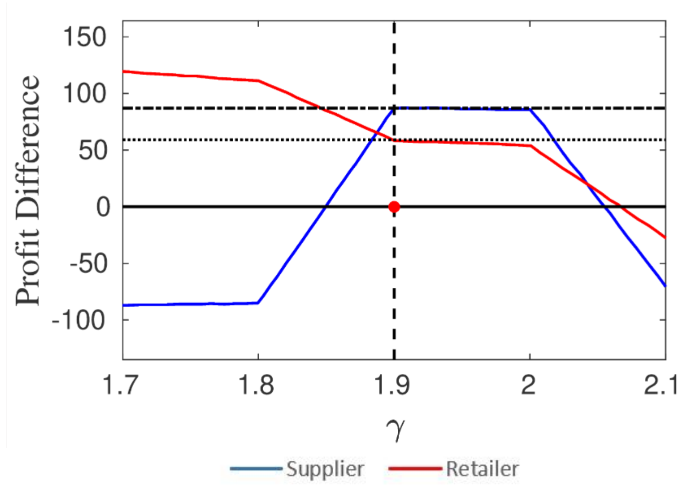

Figure 2. Expected profit- truth inducing profit for the players under optimal policy $\gamma* = 1.9$.

In Figure 2, the y-axis is the difference in players' expected profits under the cheating case and the truth-inducing policy, while the x-axis is γ. We can see that the difference is maximum for the supplier when the probability weight as 1.9 and both the players earn more than what they would do in the truth-inducing policy. Overall positions of the players under the optimal policy we find from the numerical experiments have been summed up in Figure1(iv). The vertical grid- line represents the optimal order quantity that the supplier expects from the retailer. The point at which this gridline intersects with the supplier's expected profit curve gives the optimal profit the supplier will get under this policy. A higher value of γ makes R closer to A, becomes exactly becomes A for a threshold value of γ, and won't increase further since he won't report more than A in any case. Beyond this threshold γ, only the auditing cost keeps increasing, so the supplier's profit difference turns negative.

5. Conclusion

Classical revenue-sharing contracts implicitly assume that a retailer reports the actual sales. However, evidence suggests that a rational retailer under-reports sales if he has private information in the supply chain. We investigate a two-staged supply chain in such a scenario. Our objective is to maximize supplier's profit and social welfare instead of strictly eliminating the revenue under-reporting. We use the probabilistic audit to mitigate under-reporting and derive the conditions to improve the players' expected profit from a truth-inducing policy. We analytically model the problem while arriving at the optimal audit policy using numerical simulation due to complexity. Under the optimal policy, the retailer's under-reporting may that suggests that profit maximization is a better objective than eliciting private information from the retailer.

Our results will help a manager in a supplying firm design a revenue-sharing contract when she cannot observe her retailer's revenue unless there is an audit. Our study reveals that a supplier benefits from a rational retailer's under-reporting. However, the under-reporting needs to be controlled by a probabilistic audit. This study provides guidelines to the supplying firm to set the audit probability, which optimizes her and the retailer's expected profit. We show that maximizing expected profit rather than eliciting private information from the retailer by various means, e.g., costly sales monitoring, complex contracts, etc., improves the supplier's and the retailer's pay-off.

Our study has some limitations. We did not consider the sales effort exerted by a retailer in the market. Sales effort bears a cost to the retailer. How this incurred cost will be shared between the players in the supply chain and how this sharing will impact the reporting behaviour of the retailer will be an interesting future study. We perform numerical sensitivity of only one audit function. Different forms of audit functions can be investigated, and a comparative analysis of retailers' actions will be interesting. Moreover, we did not model the retailer's different risk profiles in our model.

As future research, from a modeling perspective, one might study the effect of retailers' exerted sales effort to boost demand in the presence of competitors apropos the suggested audit mechanism. From the standpoint of numerical experiments, sensitivity to different functions for audit probability and penalty might provide some important insights.

Conflict of Interest

The authors confirm that there is no conflict of interest to declare for this publication.

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