We consider a supply chain with a supplier that sells to a retailer under a revenue-sharing arrangement. Demand is uncertain and unobservable to the supplier. We assume that the retailer is rational, that is, the retailer behaves opportunistically and underreports sales revenues to the supplier whenever such underreporting is profitable. Assuming the supplier has the ability to audit the retailer and learn about the actual sales revenues, we show that the supplier will never find it optimal to audit to the point that ensures truthful reporting for all demand realizations. By committing to an auditing policy, the supplier can exploit retailer opportunism and derive profits that at times even exceed those that could be obtained when dealing with a retailer that always strictly adheres to the agreed-upon contract terms. We also show that the retailer’s opportunistic behavior can increase total supply chain profits.

Key words: supply chain management; revenue-sharing contracts; noncooperative game theory

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1. Introduction

Firms that constitute a supply chain make decisions based on their individual incentives, which are rarely aligned with those of the overall supply chain. This incentive conflict can cause substantial inefficiencies, often associated with the concept of double marginalization, and there has been extensive research on contract mechanisms that can align the incentives of the different parties and coordinate their decisions to improve supply chain performance. The literature on coordinating contracts is very rich and Cachon (2003) provides a thorough review.

Sharing sales revenues between a seller and a supplier is one possible way to eliminate or at least mitigate the inefficiencies resulting from double marginalization, and revenue-sharing contracts are widely used in different industries, for example, in the distribution of movies, music, and video games. Sharing of revenues is also common in franchising, where manufacturers may require their retail franchisees to pay a fraction of their profits as a franchise fee (McGuire and Staelin 1986).

An implicit assumption in previous work on revenue-sharing contracts is that either the retailer, by default, always reports revenues truthfully or the supplier has the means to perfectly monitor revenues and enforce truthfulness. In the latter case, the administrative costs stemming from monitoring and contract enforcement are often not explicitly modeled.

However, in reality, perfect revenue monitoring and contract enforcement are hard to guarantee, and a retailer has both incentive and opportunity to underreport revenues to reduce the end-of-season payments to the supplier. In this study, we consider such a retailer and refer to her interchangeably as rational or opportunistic. We find evidence of retailer opportunism in various industries where revenue-sharing contracts are frequently utilized. For example, even in the video rental industry, where monitoring rental revenues is relatively straightforward and reasonably cheap due to intermediaries like Rentrak (Narayanan and Brem 2003), there have been a number of lawsuits where studios sued chains like Blockbuster and Hollywood Video for underreporting of revenues (cf. Gonzales 1999, Matzer 1998). In an example from the food industry, Dunkin’ Donuts suspected underreporting of gross sales revenues by a franchisee and took the franchisee to court for breach of contract because the amount of raw materials bought from Dunkin’ Donuts was not consistent with the reported sales (Brown et al. 2003). Underreporting of sales is observed when goods are distributed digitally through revenue-sharing contracts, too.
According to a survey conducted by the Mobile Entertainment Forum, “providers are losing as much as 10% of gross revenues due to inconsistent and inaccurate content sales reporting” (http://www.m-e-f.org, December 2007). The extent of inaccurate reporting has prompted auditing firms like KPMG to offer contract compliance services to uncover underreporting and noncompliance to contracts. While it is difficult to find data on how often underreporting is detected and how severe it is, for one company 15–20% of the audited franchise locations were found to be underreporting sales by 15% or more (http://www.audigence.com/franchise.html).

One way companies try to eliminate or curb underreporting of revenues is including audit clauses in contracts. Due to the sensitive nature of information involved, companies do not reveal the details of what triggers an audit and how an audit is conducted. However, most publicly available revenue-sharing contracts we were able to access contain similar audit clauses: they grant the company the right to audit information pertaining to the revenues collected, specify a maximum number of audits that can be conducted in a specified period of time and state that the audited party is responsible for covering the audit costs (in addition to paying any revenues due) in case the underreported revenues exceed a threshold percentage of reported revenues. For example, the revenue-sharing agreement between Buena Vista Home Entertainment (BVHE) and Hollywood entertainment gives Buena Vista the right to “audit and make copies of the books, records, invoices, and computer or database information of Hollywood as reasonably necessary to verify Hollywood’s compliance with its obligations [...] such audit shall be at the sole cost and expense of BVHE (unless such audit reveals that payments [...] were understated by more than 5%, in which case, in addition to all other rights which BVHE may have, Hollywood shall promptly reimburse BVHE to the extent of its reasonable out-of-pocket costs of such audit,) [...] BVHE may not audit more than four times per year (http://contracts. onecle.com/hollywood-entertainment/buena-vista.rsa. 1998.03.02.shtml).” The contract between Columbia Tristar Home Video and Blockbuster (http://contracts. onecle.com/blockbuster/columbia.rsa.1998.08.25. shtml) has a very similar structure, and such audit clauses also exist in contracts from other industries, for example, in diamond mining (http://www. kopanediamonds.com/i/pdf/SDD/Firestone_Canberra_ Revenue_Sharing_Agreement.pdf). In some cases, detected underreporting of revenues may even constitute a reason for contract termination. For example, the franchise contracts offered by Pita Pit state that Pita Pit may terminate the franchise agreement if a franchisee restaurant underreports gross sales by more than 3% (http://pinnaclerereholdings.com/pdf/ FDD/FDD_FA%20V31.pdf).

Much of the research on supply chain contracts focuses on the question of how to design contracts so as to achieve supply chain coordination and/or induce truthful sales reporting by the agent (the retailer). For revenue-sharing contracts, it is well known that, to achieve coordination, the supplier needs to charge a wholesale price that lies below its own cost (Cachon and Lariviere 2001). It is easy to see why firms might be hesitant to use such contracts in practice; even in the absence of opportunistic behavior, some firms might simply not be able to afford the initial financial outlays and to wait for the delayed and uncertain cash inflow at the end of the sales horizon. Experimental research also provides evidence that firms may refrain from charging wholesale prices lower than production cost. Katok and Wu (2009) study the performance of revenue-sharing contracts in a laboratory setting and observe that the median wholesale prices suppliers choose are at least as high as their production costs when average demand is low. Even in the movie rental industry, which is often cited as the most successful implementation of revenue-sharing contracts, Cachon and Lariviere (2005) state that after the implementation of revenue-sharing contracts, the price of video tapes dropped from $65 to around $8, which is clearly higher than the marginal cost to produce a tape. Hence, in this study, we approach the problem from a different perspective. For one, we explicitly focus on revenue-sharing contracts where the wholesale price covers the supplier’s production cost, thus explicitly ruling out the possibility of perfect supply chain coordination. In addition, rather than searching for a contract that induces truthful reporting by the retailer, we focus on the consequences of opportunistic behavior by the retailer.

The study is structured as follows. We review the related literature in section 2. In section 3, we describe our mathematical model. In section 4, we consider the the benchmark scenario where the supplier uses a truth-inducing auditing policy. In section 5, we characterize the retailer’s equilibrium decisions under a threshold auditing policy that leaves room for opportunism. In section 6, we construct a threshold type policy that dominates all possible truth-inducing policies, thus illustrating the impact of retailer opportunism on the supplier and the supply chain. We discuss some generalizations and extensions to our base model in section 7, and we conclude in section 8.

2. Literature Review

It is well known that revenue-sharing contracts can coordinate a single supplier–single retailer supply chain (Cachon and Lariviere 2005). One implicit
assumption in most of the related research is that the retailer always adheres to the terms of the contract and reports sales revenues truthfully, even in the absence of any enforcement. Instead, we consider a rational retailer who underreports sales revenues whenever such opportunistic behavior seems profitable. While our retailer might at times provide accurate reports, the retailer will do so only if the supplier establishes an adequate enforcement mechanism through audits and eventual penalties. The retailer is able to act opportunistically only because the supplier cannot observe demand and thus does not have complete information about the realized sales revenues. A large percentage of the literature on information asymmetry focuses on designing contracts that induce truthful information revelation. A common assumption in this literature is that a leading party (most often a Stackelberg supplier) with subjective prior beliefs regarding the distribution of retailer types makes a take-it-or-leave-it offer, in an attempt to maximize its own profits. While this setup enables the design of menus of contracts that achieve truthful information revelation, it seems to conflict with many observations of practice, where most contracts have much simpler structures than the ones proposed in this body of work. Where one party is rarely powerful, it appears to conflict with many observations of practice, where most contracts have much simpler structures than the ones proposed in this body of research, and where one party is rarely powerful enough to make a take-it-or-leave-it offer.

Rather than focusing on complex contracts that induce truth telling, we show that truth telling is not always optimal and to that aim we explicitly consider the consequences of untruthful information sharing. Untruthful information sharing has been studied in contexts such as sharecropping (e.g., De Janvry and Sadoulet 2007) and tax evasion (see Sandmo (2005) for a review). In the operations management literature, Gerchak and Khmelnitsky (2003) and Gerchak et al. (2007) model a supply chain with a single supplier and a single retailer under a vendor-managed revenue-sharing arrangement and consider the possibility that a retailer might provide the supplier with manipulated demand information. They show that untruthful information sharing results in supply chain coordination. The main difference between these two studies and the present study is that in our work, inventory is not managed by the supplier and instead the retailer places an order with the supplier before demand realization. In addition, we model supplier audits while the former two studies do not. The results of Cachon and Lariviere (1999) also suggest that untruthful information sharing can improve supply chain performance, but their model and the research questions they pursue are very different from ours. They consider a retailer and a capacity-constrained supplier operating under a wholesale-price-only contract, where the retailer places an order after observing a private demand signal. Cachon and Lariviere (1999) show that supply chain performance might improve if the retailer communicates purposefully inflated demand signals to the supplier in order to obtain a more favorable allocation.

Franchise contracts are also relevant to our work as some franchise contracts stipulate revenue sharing through royalties. The literature on franchise contracts is rich and the studies that are of interest to us allow royalty payments and model situations where the retailer has some private information, regarding the service level provided (e.g., Lal 1990, Mathewson and Winter 1985), demand (e.g., Gal-Or 1991), or a retailer-specific cost parameter (e.g., Gal-Or 1991). The main difference between this body of work and our paper is that they study whether a franchise contract can elicit truthful information from the retailer and achieve first-best outcomes while our focus is on understanding when inducing truthful information sharing may not be optimal.

As is common to the body of work that studies untruthful information sharing, we allow the retailer to behave opportunistically and underreport revenues. However, in our context, the supplier can limit or completely eliminate underreporting by auditing the retailer to the extent such actions are economical for him. Hence, the economics literature on underreporting (especially in the context of tax evasion) and auditing is relevant to our work. Examples include Townsend (1979), Border and Sobel (1985), Reinganum and Wilde (1985), and Scotchmer (1987). These studies utilize the principal–agent framework and assume that the principal can commit to an auditing scheme ex ante (as we do) and focus on auditing strategies that induce the agent to report truthfully. In Sanchez and Sobel (1993), the principal does not audit often enough to eliminate underreporting completely. In their study, this occurs because the audit budget the principal can spend is limited. We find that it is never optimal for the supplier to eliminate opportunism even if auditing is free. In our study, the retailer pays the supplier for the units bought before demand and sales revenues are realized. In the context of tax evasion, there is no such up front payment. Another difference is that these studies assume the agent cannot affect its income, whereas in our model the retailer’s order quantity choice affects the sales revenues.

Some extensions (e.g., Mookherjee and Png 1989, Weiss 1976) allow the agent to affect its income by choosing certain actions (such as how many hours to work) and find that an auditing strategy that does not completely eliminate cheating may lead to higher social welfare (Weiss 1976). A key difference between these studies and ours is that in the former, the principal cannot observe the action taken (e.g., hours worked) by the agent while in our study, the supplier...
observes the action (the order quantity chosen) taken by the retailer.

3. Model Assumptions

Consider a supply chain with a single supplier (male) and a single retailer (female). The supplier’s marginal production cost is \( c \geq 0 \). The supply chain operates under a revenue-sharing contract, under which the retailer pays the supplier a per-unit wholesale price \( w > c \) at the beginning of the period, and then—after sales have been realized at a retail price \( r - a \) fixed fraction \( z \in (0,1 - w/r) \) of the sales revenues.

The objective of our research is to study the implications of retailer opportunism in a supply chain that operates under a revenue-sharing contract. The retailer’s decisions are determined solely by the objective of profit maximization; that is, the retailer will report sales revenues untruthfully, whenever such reporting is profitable, considering the expected implications of being caught cheating. Clearly, opportunistic behavior can only be sustained in environments where some actions or market parameters are private information to one party. While such information asymmetry could be based on a number of different dimensions (e.g., the retailer’s sales effort or pricing decisions), information asymmetry in this study emerges due to the randomness of demand, realizations of which are unobservable to the supplier. We thus base our work on the classic newsvendor framework, which has been widely employed to study aspects of supply chain conflict and coordination, for example, through revenue-sharing contracts (e.g., Cachon 2003, Cachon and Lariviere 2005, Lariviere 1998). In the newsvendor framework, the retailer’s decision is how many units to purchase from the supplier. To enable a concise and elegant formulation, we assume a fixed and exogenous retail price. However, it follows directly from our analysis that our findings extend to a setting where the retailer determines the price. We study this extension in section 7.1. The key feature required for our results is that sales revenues are stochastic and unobservable to the supplier, unless he conducts an audit (cf. Proposition 3).

We let \( \xi \) denote the random demand and assume that the demand distribution \( F(\cdot) \) is differentiable and has positive support with density \( f(\cdot) \). Both the retailer and the supplier know the demand distribution \( F(\cdot) \), but it is only the retailer who observes the demand realization \( D \).

The retailer determines how many products to stock for sale to customers, and she obtains a retail price \( r \) for each product sold. For simplicity of exposition, we assume that inventory left over at the end of the sales season has no salvage value. However, all our results hold even when there is a positive salvage value, irrespective of whether the revenue-sharing contract stipulates sharing of all revenues (including those obtained through salvage) or just the regular sales revenues (at retail price); see Corollary 2 in section 7.1.

Our research focuses on the impact of retailer opportunism on a supply chain that operates under a revenue-sharing contract, and we assume that the contract terms \( (w, z) \) are given. The assumption of given contract terms is not restrictive and our key result that the supplier may benefit from retailer opportunism even after accounting for auditing costs continues to hold when the supplier sets the contract terms as Stackelberg leader (cf. Corollary 3 in section 7.2).

In the absence of any contract enforcement, the retailer would find it optimal to always report minimal sales revenues (i.e., to report zero sales at retail price). The supplier can audit the retailer to limit the retailer’s underreporting. We assume the supplier can credibly commit to an announced auditing policy that specifies the probability of an audit \( P(Q,R) \) for any given (observed) combination of order quantity \( Q \) and sales report \( R \), and a penalty function \( T(R,A) \) that specifies the transfer payment from the retailer to the supplier, when an audit reveals a discrepancy between the retailer’s report and the actual sales \( A \). We assume that the execution of audits is only based on actions in the current period, and the eventual consequences of audits only affect payoffs in the current period. We impose \( T(A,A) = 0 \), so that a truthfully reporting retailer never pays a penalty. Whenever the supplier audits with strictly positive probability, that is, when \( P(Q,R) > 0 \), we assume the retailer’s expected penalty of being caught cheating exceeds the benefit of underreporting, that is, \( P(Q,R)T(R,A) > sr(A-R) \), so a retailer would never decide to underreport when possibly facing an audit. Credible commitment is a fairly common assumption in the literature (e.g., Border and Sobel 1985, Reinganum and Wilde 1985, Scotchmer 1987, Townsend 1979) and is deemed a reasonable assumption when the designer of the policy can delegate the actual audit to a third party (Mookherjee and Png 1989). Suppliers often outsource their auditing activities to specialized firms (e.g., Audigence, KPMG, etc.), who offer tools to detect likely underreporting and non-compliance to contracts, and often perform the actual audits, so credible commitment seems to be a reasonable assumption in our context. By engaging in the business relation with the supplier, we assume the retailer has agreed to the terms of the contract, including eventual penalties for violation of these terms, and that these terms are legally enforceable. Conducting an audit costs the supplier \( K \). We omit arguments when there is no risk of confusion.
The supplier’s and the retailer’s (expected) profits are, respectively,
\[ \pi_S = E_\xi \{(w - c)Q + xR + P(Q, R)T(R, A) - P(Q, R)K \} \]
and
\[ \pi_R = E_\xi \{-wQ + rA - xR - P(Q, R)T(R, A) \}. \]

Events occur in the following sequence.
1. The supplier announces and credibly commits to an auditing policy, characterized by an auditing probability schedule \( P(Q, R) \) and a penalty function \( T(R, A) \).
2. Knowing the structure of the supplier’s announced auditing policy, the retailer sets her order quantity \( Q \).
3. Demand is realized and the retailer sells \( A \) units.
4. The retailer determines her sales report \( R \).
5. The supplier audits in accordance with the announced policy.

At each stage, the supplier and the retailer, respectively, know the (observable) outcomes from earlier stages of the game and correctly anticipate the optimal decisions at later stages. Given the knowledge at each stage, the two firms determine their decisions to maximize their respective profits as given above, where the expectation is taken with respect to demand \( \xi \). Clearly, the retailer bases her reporting strategy on the observed demand realization \( D \) (or actual sales \( A \)), rather than forming expectations over the random variable \( \xi \). (Strictly speaking, all decisions are made to maximize expected profits, as the supplier’s auditing policy specifies an audit probability.)

More formally, we define the supplier’s optimal auditing policy as follows.

**DEFINITION 1.** Let \( \Omega \) denote the set of optimal auditing policies. Then any auditing policy \( (P, T) \in \Omega \) solves the following problem.

\[
\max_{(P,T)} \pi_S(P, T, Q, R | \xi) \\
\text{s.t. } Q = \arg \max_Q \pi_R(Q, R, |P, T, \xi) \\
R = \arg \max_R \pi_R(R | P, T, Q, \xi = D).
\]

Much of the extant research has studied mechanisms with a focus on their ability to induce truthful reporting or information sharing. As a benchmark, we define the best policies with this characteristic.

**DEFINITION 2.** Let \( \overline{\Omega} \) denote the set of optimal auditing policies that induce truthful reporting. Then any auditing policy \( (\hat{P}, \hat{T}) \in \overline{\Omega} \) solves the following problem.

\[
\max_{(P,T)} \pi_S(P, T, Q, R | \xi) \\
\text{s.t. } Q = \arg \max_Q \pi_R(Q, R, |P, T, \xi) \\
R = \arg \max_R \pi_R(R | P, T, Q, \xi = D).
\]

4. Retailer Decisions and Outcomes under a Truth-Inducing Auditing Policy

In this section, we briefly discuss the retailer’s optimal decisions under an optimal truth-inducing auditing policy as described in Definition 2. Under any such policy, the retailer never underreports by definition and never pays a penalty. Hence, the problem reduces to the standard newsvendor problem. Specifically, the retailer’s expected profit function and optimal order quantity \( Q \) are given by

\[
\bar{\pi}_R = -wQ + (1 - x)r \\
\times \left( \int_0^Q Df(D)dD + \int_Q^{\infty} Qf(D)dD \right) \text{ and } (1)
\]

\[
\bar{Q} = F^{-1}\left(\frac{(1 - a)r - w}{(1 - a)r}\right). \tag{2}
\]

With a truth-inducing auditing policy \( (\hat{P}, \hat{T}) \), the retailer reports the actual sales \( A = \min(Q, D) \), and the supplier’s expected profit can be written as

\[
\hat{\pi}_S = (w - c)\hat{Q} + \int_0^{\hat{Q}}(xrD - K\hat{P}(\hat{Q}, D))f(D)dD \\
+ \int_{\hat{Q}}^{\infty}(xr\hat{Q} - K\hat{P}(\hat{Q}, \hat{Q}))f(D)dD. \tag{3}
\]

5. Retailer Decisions and Outcomes under a Threshold Auditing Policy

In this section, we characterize the retailer’s optimal decisions under a threshold auditing policy, under which the supplier audits the retailer with probability \( P(Q, R) \) if the retailer’s reported sales \( R \) are smaller than the minimum of the retailer’s order quantity \( Q \) and a threshold \( B \). Otherwise, the supplier does not audit, or \( P(Q, R) = 0 \). When an audit reveals that the retailer has underreported sales revenues, the supplier charges a penalty \( T(R, A) \), which is set sufficiently high to ensure that the expected cost of cheating is higher than the expected benefit. We later
show that auditing policies of such threshold structure are optimal, so our focus on threshold auditing policies is without any loss of generality.

We use backward induction to determine the supplier’s and the retailer’s equilibrium decisions. To simplify the exposition, in the following we omit the modifier expected, that is, we use profits and sales to denote expected profits and expected sales, etc.

Consider the retailer’s reporting decision. As the supplier has committed to auditing if and only if reported sales are below the minimum of the retailer’s order quantity \(Q\) and the threshold \(B\), the retailer will never report sales in excess of the smaller of \(Q\) and \(B\), so \(R < \min(Q,B)\). If demand is smaller than \(\min(Q,B)\), the retailer knows that the supplier audits and has no interest in underreporting (because the penalty for being caught cheating is sufficiently high in expectation to ensure a retailer never submits a false report before possibly facing an audit). The retailer clearly never has incentive to overreport sales to avoid an audit as such an audit would be without consequence if she reported truthfully. Hence, the retailer’s optimal reporting strategy is

\[
R^* = \min(D, Q, B). \tag{4}
\]

Note that following this strategy, an audit will never reveal dishonest reporting. Under the given auditing strategy, the supplier leaves no room for cheating when the retailer’s demand is less than \(B\), whereas he knowingly allows cheating when demand is greater than \(B\). A direct consequence of this observation is that the specific value of the imposed penalty for discovered underreporting is irrelevant, as long as the bracketed term in \(\pi_{R_1}(Q)\) is strictly decreasing in \(Q\), whereas \(\pi_{R_1}(Q)\) is constant in \(Q\) and \(\pi_{R_1}(Q)\) is strictly decreasing in \(B\). Specifically, as \(B\) increases to \(Q_2\), the bracketed term in \(\pi_{R_1}(Q_2)\) vanishes and we have \(\pi_{R_1}(Q_2) = \pi_{R_1}(Q_2) < \pi_{R_1}(Q_1)\). Hence, there exists a unique threshold \(B\) that is defined through the following equation.

\[
\pi_{R_1}(Q_1|B) = \pi_{R_1}(Q_2|B). \tag{9}
\]

The threshold \(B\) cannot be smaller than \(Q_1\), as the retailer then always would prefer to order \(Q_2\), which contradicts the assumptions underlying cases 1 and 2. On the other hand, the threshold \(B\) cannot be greater than \(Q_2\), as otherwise the retailer would prefer to report truthfully, that is consistent with her order quantity \(Q_2 < B\), but the optimal order quantity for a truthfully-reporting retailer is \(Q_1\). Hence, it must be true that \(Q_1 \leq B \leq Q_2\), and the retailer’s optimal order quantity is

\[
\pi_{R_1}(Q) = -wQ + (1-x)r \left( \int_0^Q Df(D) dD + \int_Q^\infty Qf(D) dD \right) \text{and}
\]

\[
Q_1 = F^{-1}\left(\frac{(1-x)r-w}{(1-x)r}\right). \tag{6}
\]

Note that, as expected, the retailer’s optimal order quantity under case 1 is equivalent to the optimal order quantity under the truth-inducing auditing policy, that is, \(Q_1 = Q\).

When \(Q \geq B\) (case 2), the retailer will always find it beneficial to underreport sales revenues for some demand realizations. The retailer’s profit function for this case is

\[
\pi_{R_2}(Q) = \pi_{R_1}(Q) + xr \left( \int_B^Q (D-B)f(D) dD + \int_Q^\infty (Q-B)f(D) dD \right). \tag{7}
\]

It is easy to show that this function is concave in \(Q\) and that the retailer’s profit maximizing order quantity is given by

\[
Q_2 = F^{-1}\left(\frac{r-w}{r}\right). \tag{8}
\]
We see that, at the margin, an opportunistic retailer associates 100% (rather than just her agreed-upon fraction $1 - z$) of the profit margin with stocking additional units. In essence, when ordering a sufficiently large quantity, the retailer’s incentives resemble those under a wholesale-price-only contract. However, note that the retailer still shares some sales revenues with the supplier. Hence, while the retailer’s order quantity is set based on the same critical fractile, the allocation of profits between the retailer and the supplier will differ from that under a wholesale-price-only contract because some sales revenues are shared. As $Q_2$ is larger than $Q_1$, but smaller than the supply-chain-optimal order quantity (as $w > c$), the retailer’s opportunistic behavior mitigates double marginalization and improves supply chain performance for sufficiently small auditing cost. In the next section, we show that, with the appropriate auditing policy, even the supplier may benefit from retailer opportunism.

**6. Auditing in the Presence of Retailer Opportunism**

While much of the extant research has focused on designing mechanisms that induce truthful information transfer, in this study, we explicitly consider auditing policies that leave room for opportunistic behavior and show that a focus on truth-inducing mechanisms might be too narrow. In the following, we focus on one of the supplier’s best truth-inducing policies as given in Definition 2 and construct a modified policy (of threshold type) which leaves room for opportunistic behavior. We show that supplier profits are higher under this modified policy than under any optimal truth-inducing policy, thus proving that the optimal auditing policy is not truth inducing.

All truth-inducing policies yield the same revenues for the supplier and differ only by the auditing cost. The best truth-inducing auditing policies $(\tilde{P}, \tilde{T}) \in \Omega$ thus are those with the lowest auditing cost. In the following, we modify one of these best optimal truth-inducing policies such that it leaves room for underreporting and we show that this modification leads to strictly higher supplier profits. Define

$$Q^* = \begin{cases} Q_1 & \text{if } B > \bar{B}, \\ Q_2 & \text{otherwise.} \end{cases}$$  \hspace{1cm} (10)$$

Following backward induction, we first derive the retailer’s optimal reporting strategy $R$ under $(\tilde{P}, \tilde{T})'$ for any $Q$. If $Q \leq \bar{Q}$, the reporting strategy is clearly the same as that under the truth-inducing strategy as it is never optimal for the retailer to report more than it sells. For $Q > \bar{Q}$, consider the case where $A \leq \bar{Q}$. For these sales realizations, the benefit from cheating is $x r (A - R) - B (R, A)$. These costs and benefits of cheating are the same for retailers that order $\bar{Q}$ and $Q > \bar{Q}$ and as the optimal strategy for the former is truth telling by definition, truthful reporting is optimal for the latter, too. When $A > \bar{Q}$, the retailer can always avoid an audit by reporting $\bar{Q}$ and the previous argument directly implies that the retailer has no incentive to report less than $\bar{Q}$. Hence, the retailer’s optimal reporting strategy is $R^* = \min (D, Q, \bar{Q})$. Note that we cannot simply use Equation (4) with $B = \bar{Q}$ to derive this result, as, after fixing the audit probability schedule, our assumption of sufficiently severe penalties for cheating is not necessarily maintained.

Under the auditing policy $(P, T)'$, we have $B = \bar{Q} \leq B$, so it follows from Equation (10) that the retailer’s optimal order quantity is $Q_2$.

Finally, we show that the supplier’s profit is higher under $(\tilde{P}, \tilde{T})'$ than under the best truth-inducing auditing policy. No retailer will be caught cheating under either $(\tilde{P}, \tilde{T})$ or $(P, T)'$ and $T(A, A) = 0$, so we do not have to consider the cheating penalty function $T$.

Under the best truth-inducing policy $(P, \tilde{T})$, the supplier’s profit is given by Equation (3). As $B = \bar{Q} \leq B \leq Q_2$, under the constructed policy $(P, \tilde{T})'$, the supplier’s profit is

$$\pi_{S_2} = (w - c)Q_2 + \int_0^\bar{Q} (x r D - K P (\bar{Q}, D)) f(D) dD + \int_\bar{Q}^\infty x r \tilde{Q}(D) dD.$$  \hspace{1cm} (12)$$

Considering the difference between Equations (3) and (12), we see that, under the constructed policy $(P, \tilde{T})'$, the supplier’s up-front revenues are strictly higher as $(w - c)Q_2 > (w - c)\bar{Q}$, his share of sales revenues,

$$\left( x r \left( \int_0^\bar{Q} D f(D) dD + \int_\bar{Q}^\infty \tilde{Q}(D) dD \right) \right),$$

is the same as before, and his auditing cost is no higher than under $(P, \tilde{T})$—for all reports below $\bar{Q}$, the two policies audit with equal probability (for realizations in this region stock-outs are not a con-
cern, so both the retailer facing the truth-inducing policy and the one facing the modified policy report the actual demand realization), and for reports above \( Q \), the constructed policy does not prescribe any audits.

As the modified auditing policy is contained in the set of admissible auditing policies, it can thus never be optimal for the supplier to completely eliminate opportunistic behavior, which proves the following result. (If there does not exist a solution to the problem defined in Definition 2, the statement in Theorem 1 clearly is true.)

**Theorem 1.** There does not exist an optimal auditing policy that induces truthful reporting; that is, \( \Omega \cap \Omega = \emptyset \).

At first sight, Theorem 1 seems counterintuitive. It states that, irrespective of the cost of auditing, the supplier will never find it optimal to establish an auditing policy that completely eliminates retailer opportunism. Even if auditing were free, the supplier would prefer not to audit for all reported sales realizations because giving the retailer some room for opportunism leads to higher system profits, some of which can always be extracted through limited auditing. When the retailer has the ability to underreport revenues, her incentives become more aligned with that of the chain, which results in an increase in supply chain profits. The primary driver for this result is the reduction in double marginalization that occurs when the retailer anticipates underreporting in high-demand scenarios and thus internalizes 100% of her profit margin, rather than the agreed-upon fraction \( 1 - \alpha \). As the retailer’s order quantity increases and internal transfer payments are irrelevant from a supply chain perspective, it is not surprising that retailer opportunism has a positive impact on the aggregate supply chain (prior to accounting for auditing costs).

Theorem 1 demonstrates that any optimal policy leaves room for cheating. In the following two results, we provide some more specific structural insights into the supplier’s optimal auditing policy. Assume that we consider the class of auditing policies that can be defined by an audit probability schedule \( P(Q,R) \) and a penalty function \( T(R,A) \). The following result proves that there always exists an optimal auditing policy of threshold structure.

**Proposition 1.** For any order quantity \( Q \), there exists an optimal auditing policy that has a threshold structure, such that no audits are conducted for any report at or above \( B(Q) \), and for all reports below \( B(Q) \), the supplier audits with strictly positive probability \( P(Q,R) \).

**Proof.** By assumption, the supplier chooses a penalty function that ensures that the retailer will never submit an untruthful report when possibly facing an audit, that is, when \( P(Q,R) > 0 \). For any \( Q \), Theorem 1 then implies that it is not optimal to audit for all possible sales realizations, so there exists some sales report \( R < Q \) for which \( P(Q,R) = 0 \). Let \( X(Q) \) denote the smallest sales report with \( P(Q,R) = 0 \). If the supplier does not audit at all, the retailer orders \( Q_2 \) and always reports \( R = 0 \), leaving the supplier without any additional revenues besides those received upfront. As the supplier can extract some additional revenue without causing the retailer to order less than \( Q_2 \) (cf. Equation (10) and recall that \( B \geq Q_1 > 0 \) by auditing for low sales reports, in any optimal policy, it must hold that \( X(Q) > 0 \). Consider the retailer’s reporting strategy for a given sales realization. The penalty for being caught cheating is sufficiently high (in expectation), so a retailer never submits a false report when possibly facing an audit. Hence, if the retailer underreports, she reports the smallest possible realization that does not trigger an audit, that is \( X(Q) \). As the retailer would never submit an untruthful sales report that is larger than \( X(Q) \), it is one optimal strategy for the supplier not to audit for reports with \( R > X(Q) \). We thus have \( P(Q,R) = 0 \) for \( R \geq X(Q) \) and \( P(Q,R) > 0 \) for \( R < X(Q) \), which proves that a threshold policy with \( B(Q) = X(Q) > 0 \) is an optimal policy.

Having the option to behave opportunistically clearly always benefits the retailer (at least weakly). If auditing is free, one consequence of Theorem 1 is that such opportunism increases supply chain and supplier benefits, as it partially aligns incentives and brings the retailer’s order quantity closer to the supply chain optimal order quantity. Indeed, continuity of the supplier’s profit functions in the cost of auditing \( (K) \) directly implies that the supplier and the supply chain will benefit if the expected auditing costs are sufficiently low.

However, even if every audit is associated with a significant cost, that is, even if \( K \) is substantial, the supplier (and thus the supply chain) can benefit from opportunistic retailer behavior, if the retailer is indeed fully rational and bases her decisions on the associated expected consequences. The supplier then can make his expected auditing costs arbitrarily small by reducing the audit probabilities and using sufficiently harsh penalties to ensure that the mere possibility of an audit deters underreporting by the retailer. Specifically, the supplier only needs to ensure that, whenever \( P(Q,R) > 0 \), \( P(Q,R)T(R,A) > \alpha(A - R) \), such that, when facing an audit with positive probability, the retailer’s benefits from cheating are always smaller than the expected penalty.
If expected auditing costs can be made arbitrarily small, Theorem 1 directly implies that there exists an auditing policy, under which opportunistic retailer behavior increases supplier and supply chain profits, when compared to the scenario with an honest retailer that always adheres to the terms of the contract. Under the assumption that the expected auditing costs can indeed be made arbitrarily small, we can determine the optimal auditing threshold for the policy described in Proposition 1. For reports below \( B \), the supplier then should announce very low audit probabilities coupled with sufficiently harsh penalties to ensure that the retailer never underreports when possibly facing an audit.

**Proposition 2.** If the expected costs of auditing can be made arbitrarily small, a threshold policy with \( B = B^* \), as defined in Equation (9), is optimal.

**Proof.** Given a (any) threshold auditing policy, the retailer either orders such that truthful reporting is optimal for all demand realizations \((Q < B)\) or the retailer orders such that it can keep the full sales revenues on some demand realizations \((Q \geq B)\). Recall that \( T(A, A) = 0 \) and that the expected penalty for (possibly) being caught cheating is sufficiently large to deter untruthful reporting. Marginal analysis then directly implies that the retailer uses quantities \( Q_1 \) and \( Q_2 \) (as defined in Equations (6) and (8)) under these two scenarios, respectively. As outlined in the study, under revenue sharing and given \( w > c \), an auditing policy with \( B < Q_1 \) cannot be optimal as it is strictly dominated by some policy with \( B \geq Q_1 \). To induce the higher order quantity \( Q_2 \), the supplier needs to maintain \( B \leq B^* \). As, given \( Q_2 \), the supplier’s expected profit increases in \( B \), the supplier’s optimal auditing threshold is \( B^* \).

The observations above directly imply the following corollary to Proposition 2.

**Corollary 1.** Under any optimal auditing policy \((P, T) \in \Omega\), retailer opportunism increases supplier and supply chain profits compared to the scenario with an honest retailer that always adheres to the terms of the contract.

As retailer opportunism increases supply chain profits and as the supplier can make his expected auditing costs arbitrarily small, the supplier can always benefit from the retailer’s consideration of opportunistic reporting. Even though the retailer has private information and can report opportunistically, when the supplier uses an optimal auditing policy, he extracts all benefits from the retailer’s opportunistic deliberations and he leaves the retailer with the same expected profits that she could have obtained by ordering \( Q_1^* \) and reporting honestly.

### 7. Generalization & Extensions

In section 7.1, we demonstrate that our main results can be derived based on a much more general argument, allowing us to relax many of the assumptions that we made in the main part of the study for expositional simplicity. Among other things, this generalization directly implies that our results apply when retail prices are endogenous, and when the retailer has access to a salvage market, irrespective of whether salvage revenues are shared or not (cf. Corollary 2). In section 7.2, we prove that our insights also apply when the terms of the revenue-sharing contract are set by the supplier.

#### 7.1. Generalization of our Argument

In the following we show that our key result, that the supplier will never find it optimal to establish an auditing policy that induces truthful reporting, also applies if the retailer can make unobservable pricing adjustments after observing the state of the market (demand curve). We focus on pricing adjustments made after observing the state of demand as pricing decisions made prior to demand realization can be perfectly anticipated or inferred by the supplier through the order quantity, even if the supplier does not observe prices directly. Besides the additional stage where the retailer determines the sales price, we assume the same sequence of events as in the main part of the study, that is, (i) the supplier establishes an auditing policy \((P, T)\), (ii) the retailer determines the order quantity \( Q \), (iii) nature reveals the state of demand \( D \), (iv) the retailer sets the sales price \( r \), (v) the retailer realizes sales revenues \( S \), (vi) the retailer reports sales revenues \( R \), and (vii) the supplier conducts audits consistent with the announced ordering policy.

Two observations follow directly. First, as the retailer always benefits from increased sales revenues, given an order \( Q \) and an observed demand state \( D \), the retailer sets the retail price \( r(Q, D) \) that maximizes sales revenues \( S \), irrespective of the prevailing auditing policy. (If there are multiple sales-revenue-maximizing retail prices, then the retailer uses one of those.) Then, given the retailer’s optimal pricing strategy \( r^*(Q, D) \), the expected sales revenues \( E_i(S|Q) \) are an increasing function of \( Q \). Note that, while both the supplier and the retailer have full information and can, ex ante, perfectly anticipate the optimal pricing strategy \( r^*(Q, D) \), the supplier cannot observe the retailer’s (realized) pricing decision.

As before, consider the retailer’s equilibrium behavior under the (or any) auditing policy that
induces truthful reporting. The retailer then determines the optimal order quantity \( Q \) by maximizing her profits

\[
\pi_R(Q) = -wQ + (1 - x)E_S(S|Q).
\]

Assume that \( \pi_R(Q) \) is well-behaved and that the first-order condition is necessary and sufficient (this always holds if expected sales revenues are concave increasing in the order quantity). The first-order condition then implies that

\[
\left[ \frac{\partial\pi_R(Q)}{\partial Q} \right]_{Q=\hat{Q}} = -w + (1 - x)\frac{\partial E_S(S|Q)}{\partial Q} = 0. \tag{13}
\]

Consider the case where auditing is costless. (It can easily be shown that our argument continues to hold in the presence of auditing costs; cf. proof of Theorem 1.) A truth-inducing auditing strategy then cannot be optimal, as there exists an auditing policy that, given the same contract parameters \( \{w, \bar{x}\} \), leads to a higher retailer order quantity and, in expectation, the same reported sales revenues.

We show that any policy that induces truthful reporting of sales revenues can be improved upon by leaving some room for cheating. Specifically, we show that there exists a threshold auditing policy that leaves room for opportunistically reporting and dominates any policy that induces truthful reporting of sales revenues.

As the optimal pricing strategy \( r^*(Q,D) \) is common knowledge and sales revenues for any given order quantity \( S(D|Q) \) are strictly increasing in the demand realization, there exists an inverse function \( D(S|Q) \) that relates any reported sales revenue back to the underlying demand realization. Given this one-to-one correspondence between sales revenue reports and the demand realization, the auditing threshold can be defined in terms of sales revenues or, equivalently, in terms of the corresponding demand realization. For consistency with our exposition throughout the main part of the study and without loss of generality, we define the auditing policy threshold in terms of the demand realization, and we assume an auditing policy with threshold \( B = \hat{Q} \) (implying an audit when reported sales revenues are below \( S(Q) \)). Under such a policy, the retailer’s profit equals

\[
\pi_R(Q|B = \hat{Q}) = -wQ + (1 - x)E_S(S|Q) + \bar{x}E_S([S - B]^+|Q),
\]

where \( E_S([S - B]^+|Q) \) is non-negative and strictly positive for all non-degenerate demand distributions. Evaluating the first-order condition at \( \hat{Q} \), we have

\[
\left[ \frac{\partial\pi_R(Q|B = \hat{Q})}{\partial Q} \right]_{Q=\hat{Q}} = \left[ \frac{\partial\pi_R(Q)}{\partial Q} \right]_{Q=\hat{Q}} + \bar{x} \left[ \frac{\partial E_S([S - B]^+|Q)}{\partial Q} \right]_{Q=\hat{Q}} = 0 + \bar{x} \left[ \frac{\partial E_S([S - B]^+|Q)}{\partial Q} \right]_{Q=\hat{Q}} > 0,
\]

so the retailer increases the order quantity while, in expectation, reporting the same sales revenue. As \( w > c \), the supplier is strictly better off than under truthful reporting.

These observations prove the following result.

**Proposition 3.** Theorem 1 continues to hold if the retailer can adjust the retail price after observing the state of the market (demand).

While we have based the preceding argument on the example of a retailer deciding the retail price after observing the state of demand, it follows directly that our results hold in a variety of settings. In essence, our argument requires these settings to satisfy only the following two characteristics. First, the ex ante expected sales revenues \( E_S(S|Q) \) are a concave increasing function of the retailer’s order quantity \( Q \) (implying that the retailer’s order quantity is determined by the first-order condition in Equation (13)), and this functional relation is common knowledge. Second, while both parties can evaluate the expected sales revenues, only the retailer can observe the revenue realization.

Our results also hold if the retailer can salvage leftover units at a positive salvage value \( 0 < s < w \), irrespective of whether these salvage revenues are shared with the supplier (with the same fraction \( \bar{x} \)) or not. In the study, we constrain the supplier’s revenue share parameter \( \bar{x} \) to be such that \( (1 - \bar{x})r > w \), guaranteeing a strictly positive profit margin for the retailer. As \( w > s \), it is ensured that \( (1 - \bar{x})r > s > (1 - \bar{x})s \), so salvaging units is always strictly less profitable to the retailer than selling on the primary market. Hence, even with a salvaging opportunity, it holds that expected sales revenues are an increasing function of the retailer’s order quantity and that realized sales revenues strictly increase in the demand realization. As before, expected sales revenues (both on the primary market and through salvage) can be anticipated by both parties, while only the retailer observes the demand (and revenue) realization. A direct implication of these observations is that the argument above applies, proving the following corollary to Proposition 3.
Revenue-sharing contracts are widely used in practice to align incentives in a supply chain. Much of the extant research on revenue sharing has been based on the assumption that retailers always report sales truthfully. However, there is substantial evidence of opportunistic reporting of sales revenues, especially in industries where perfect monitoring of revenues is impossible or prohibitively expensive. In addition, research to date has focused on supply chain coordination and for revenue-sharing contracts such coordination requires suppliers to sell below cost. However, many suppliers may not be willing to sell below cost because it may not be financially viable for them to incur a loss up front and collect delayed and uncertain payments later, or they may simply refuse to take on enough risk to coordinate the channel, especially when average demand is low (Katok and Wu 2009).

We explicitly consider a supply chain where coordination using revenue-sharing is not possible because the supplier will not sell below cost and the retailer is rational, that is, the retailer underreports revenues whenever such underreporting leads to higher (expected) profits. Interestingly, we find that such retailer opportunism can increase supply chain profits, as the retailer internalizes the full potential marginal sales revenue, rather than just her contractually agreed-upon fraction, increasing her order quantity and mitigating double marginalization. We show that it is never optimal for suppliers to completely eliminate such opportunistic behavior through auditing, even if auditing is free of cost. The supplier benefits from retailer opportunism because the opportunistic retailer places a larger order.

Hence, rather than as a tool to completely eliminate underreporting, suppliers should view auditing as a means of limiting opportunistic behavior and extracting additional profits. Our results are important because they show that suppliers can use revenue-sharing contracts even when the retailers are opportunistic as long as the suppliers can utilize auditing to keep cheating at bay. When facing opportunistic retailers, it may seem that the best option for suppliers is to offer a wholesale-price-only contract that does not leave room for opportunism. However, our results show that, when combined with an appropriately-designed auditing mechanism, a revenue-sharing contract outperforms any wholesale-price-only contract.

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