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Execution Quality and Chargeback Penalties in Retail Supply Chains

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Abstract

Retailers procure inventory by placing purchase orders (POs) with suppliers. POs specify product price, quantity, quality, delivery times, and other aspects of the fulfillment process, such as carton labeling requirements and packaging formats. When servicing an order, a supplier may fail to meet the fulfillment terms, thus committing a fulfillment error and triggering a chargeback penalty. We collect supplier compliance manuals from 111 retailers to characterize fulfillment errors and chargebacks in practice. The majority of chargeback penalties listed by retailers pertain to *execution quality*: aspects of the fulfillment process beyond product price, quantity, quality, and delivery time. We use an empirically grounded analytical model in combination with game-theoretic analysis to demonstrate that the chargebacks most commonly used in practice do a poor job coordinating supply chains around execution quality. This result contradicts the recommendations in the trade literature.

1 Introduction

Retailers procure inventory by placing purchase orders (POs) with suppliers. POs specify product order quantities and delivery times as well as other aspects of the fulfillment process such as carton labeling, electronic data interchange, bar code standards and placement, product packaging, and transportation. Execution of the fulfillment terms is instrumental for modern supply-chain techniques, such as cross-docking and pack-by-store, as well as for automation, such as robots supplied by Kiva Systems.

When filling a PO, a supplier may violate the terms of the PO, thus committing a fulfillment error. Fulfillment errors are common in practice. Craig et al. (2015) find fulfillment errors associated with nearly 7 % of the POs of a large retailer. Retailers penalize suppliers for fulfillment errors by issuing chargeback penalties, or chargebacks. Chargebacks reduce supplier revenue by 2 % to 10 % annually (Zieger, 2003), thus transferring billions of dollars from suppliers to retailers.

Chargeback penalties have long been contentious among retailers and vendors, with practitioners viewing the penalties as everything from necessary for supply-chain performance to an underhanded means for preserving retail margins (Hays, 2001). Nonetheless, the use of chargeback penalties appears to be increasing among retailers (Ryan, 2018). Major retailers, including Amazon (Stevens et al., 2018), Target (Bose and Layne, 2016), and Walmart (Berman, 2016), have increased the stringency of their fulfillment requirements and the magnitude of their chargebacks in attempts to improve inventory accuracy, reduce procurement costs, and support omnichannel strategies.

Research on fulfillment in retail supply chains concentrates on product price, quantity, and product quality as well as timely delivery. Although those aspects of fulfillment are vital, retailer POs specify numerous other fulfillment requirements. To understand the range of fulfillment errors and chargeback penalties retailers use in practice, we study the supplier compliance manuals of 111 retailers. Retailers list fulfillment requirements as well as penalties for specific errors in these manuals.

The majority of fulfillment errors addressed in supplier compliance manuals do not involve price, product quantity, product quality, or delivery time. Instead, the majority of errors in the compliance manuals involve peripheral aspects of the fulfillment process itself. Examples include suppliers incorrectly packaging product, failing to transmit an advance shipping notice (ASN), violating ergonomic requirements regarding carton weight and dimensions, or adhering carton bar codes incorrectly. Hence, in addition to contracting for product price, quality, quantity, and delivery time, retailer POs contract for execution quality. We use the term *execution-quality errors* to refer to fulfillment errors not involving price, product quantity or quality, or delivery time.

Researchers present chargebacks as a mechanism for aligning firm and supplier incentives regarding product quantity (Tsay, 2001; Cachon, 2003) or quality (Reyniers and Tapiero, 1995; Baiman et al., 2000). They argue that chargebacks allow firms within a supply chain to distribute the costs of quantity errors (e.g., shortage and overage costs) and of quality errors (e.g., warranty replacements). In contrast, we study chargebacks as a means for sharing costs—and aligning incentives—with respect to execution quality, which is a major concern in practice. Execution-quality errors require the retailer to incur costs associated with rework: e.g., inspecting a shipment that arrives without an ASN to determine the shipment's identity, or affixing corrected tickets (i.e., price tags) if a supplier uses incorrect tickets. Craig et al. (2015) find that chargebacks for execution quality account for 60 % of the dollar value of all chargebacks issued by a retailer.

From the perspective of supply-chain coordination, the purpose of chargeback penalties is to induce the supplier to invest in the level of execution quality that minimizes the supply chain's costs related to execution quality. For example, if poor execution quality is expensive for the retailer but inexpensive for the supplier to remedy, then it can be more efficient for the supplier to address execution quality issues. Large chargebacks that reflect a high cost of inferior execution quality to the retailer should induce the supplier to increase its execution quality when doing so is less expensive than incurring the chargebacks. Hence, chargeback penalties act as a signal that the retailer conveys to the supplier to motivate supplier investment in execution quality where it provides the most benefit to the supply chain.

We ground our study on empirical observations, specifically, the penalties retailers specify in their vendor compliance manuals. We develop a model of the cost impact of execution-quality errors on a retailer's inventory system. We find that common chargebacks do not reflect the cost impact of a supplier's execution quality on a retailer's inventory system. Our numerical study reveals that the chargeback associated with an execution-quality error deviates from the true cost of the error by between 38 % and 75 %, on average, depending on the type of the chargeback penalty.

The trade literature argues that simple chargebacks improve supplier compliance. For example, Atkinson (2007) writes "keeping your chargeback program consistent and simple should be another of your key goals" (p. 40). Simple chargebacks may also support resolution of chargeback disputes by obviating complex arguments regarding the appropriate chargeback for a given compliance issue. Our empirical analysis reveals that many retailers implement such programs and use fixed, per-incident penalties that do not vary across products. However, our model shows that such chargeback policies are inadequate mechanisms for communicating the cost of lapses in execution quality.

The effectiveness of chargebacks as mechanisms for coordinating execution quality in a given supply relationship depends not only on the accuracy of the chargebacks but also on the interactions between the decisions of the retailer and the supplier. We formulate a game in which the retailer sets a chargeback policy and the supplier responds by selecting a level of execution quality, where higher quality is costly to the supplier. Moreover, depending on the supplier's power within the relationship, the supplier may recover some portion of the revenue it loses to chargebacks by increasing price. The analysis of the parties' decisions shows how misaligned incentives for execution quality affect the performance of a supply chain and the outcomes for its constituent firms, not only directly but also through interactions with other aspects of a supply relationship.

2 Literature Review

Our research is closely related to studies that address fulfillment errors, supply-chain incentives, and supply-chain contracting. Prior research on fulfillment errors in supply chains characterizes the prevalence of fulfillment errors in practice and distinguishes fulfillment errors from related types of errors, such as production process errors. Srinivasan et al. (1994) examine "shipping discrepancies" among suppliers to an automotive manufacturer. The discrepancies include execution-quality errors, such as incorrect shipment documentation, and affect 12 % of supplier shipments on average. A survey of 42 retailers found that 13 % of inbound shipments experienced a particular execution-quality error, namely an inaccurate ASN (Retail VCF, 2010).

Craig et al. (2015) found that over half of fulfillment errors related to execution quality. These execution-quality errors included invalid reference numbers or incorrect labels or tickets (Ma, 2013). Speh (2001) found in observing 45 distribution centers for pharmaceutical supply chains that 5 % of orders were subject to execution-quality errors. Such errors have been shown to reduce trust (Poppo et al., 2008).

It is generally assumed that chargebacks allow firms to elicit the optimal production quality (e.g., Cachon (2003)) or to share the costs associated with poor product quality. Tsay (2001) and Lee and Rhee (2008) evaluate chargebacks as a means of sharing the supply-chain cost of unsold inventory and discounts. Other researchers examine contracting for product quality. Reyniers and Tapiero (1995), Baiman et al. (2000), Lim

(2001), and Jin et al. (2014), for example, explore the costs of warranty replacements and scrap wherein chargebacks allow firms to share the cost of poor product quality, e.g., the costs of warranty replacements and scrap. In contrast to supply-chain research that is aimed at eliciting the optimal production quantity or product quality, our objective is to understand chargeback penalties as incentives for execution quality.

The incidence of errors in a fulfillment context can differ from that in a production context. Prior research focuses primarily on production settings under random yields (see Yano and Lee (1995) for a review), wherein errors do not depend on lot size (Peters et al., 1988; Zhang and Gerchak, 1990; So and Tang, 1995; Jamal et al., 2004; Eroglu and Ozdemir, 2007). Other researchers assume that production processes may transition to an out-of-control state while manufacturing each unit, in which case the proportion of products that experience errors increases with lot size (Porteus, 1986; Lee, 1992). In contrast, empirical research in a retail fulfillment setting shows that the proportion of errors decreases with order quantity (Craig et al., 2015). Herein, we show how assumptions about the relationship between the incidence of errors and order quantities affect inventory decisions.

3 Execution-Quality Errors and Chargebacks

Retailers often specify fulfillment errors and associated chargebacks in supplier compliance manuals. In this section, we use supplier compliance manuals to characterize the form of chargebacks for execution-quality errors across a variety of supply chains. We collected manuals from 111 major retailers based in the United States. For each of the manuals, we extracted all chargeback penalties listed by the retailers. Specifically, we identified the fulfillment error that triggered each chargeback as well as the type and magnitude of the associated penalty.

The majority of the retailers we study are department stores (36), apparel stores (24), household goods stores (17), and electronics stores (10), where we define retail segments using four-digit NAICS codes. The remaining retailers include convenience stores, drugstores, grocery stores, office supply stores, and sporting goods stores. The revenues of the retailers we examine range from approximately $0.5 B to over $100 B for the year in which we collected each retailer's manual.

We identify a total of 63 distinct fulfillment errors across all compliance manuals. We group the fulfillment errors into categories, such as "Transportation," "Bills of lading," and "Pack-by-store." Table 1 summarizes the categories, the number of errors associated with each category, and provides an example fulfillment error from each category. Of the 63 fulfillment errors, 54 are execution-quality errors—i.e., errors that do not involve product price, product quality, product quantity, or delivery time.

The chargebacks listed by the retailers comprise different types of charges. For example, in the event that a supplier's products have incorrect universal product codes (UPCs), one chain of department stores issues a chargeback of $25 plus $0.50 per affected unit. A competing chain issues a fixed chargeback of $150 for the same error. If a supplier packages merchandise in bulk when the PO specifies pack-by-store, one apparel retailer issues a charge equal to 10 % of the PO cost. A similar retailer issues a flat fee of $450.

The retailers structure their chargebacks using combinations of three types of charges: a fixed charge, a charge that scales with the quantity of affected units, and a charge equal to a percentage of the value (measured at cost) of all products on the PO. A single retailer may use multiple types of charges. For example, one retailer assesses a $150 fixed charge for a missing or incorrect ASN. In the case of incorrect tickets, the same retailer levies a $150 fixed charge plus $1 per affected unit.

To illustrate the prevalence and magnitude of each chargeback penalty type (fixed charge, per-unit charge, and value-proportion charge), we present in Table 2 the five

Table 1: Fulfillment error categories and examples.

Fulfillment Error Category	**Count of Fulfillment Errors**	**Count of Execution-Quality Errors**	**Example of Category**
Transportation	12	10	Shipping by non-preferred freight carrier
Shipment timing	2	0	Shipment shipped after the cancellation date on the purchase order
Bills of lading	9	9	No special handling requirements note for hazardous items
Packing lists and advance shipping notices	7	7	Missing packing list
Pallet issues	1	1	Incorrect pallet type
Product packaging and labeling	10	10	Use of incorrect hangers or missing clamshell anti-theft packaging
Pre-ticketing	4	4	Incorrect or missing universal product codes
Carton packing and labeling	6	6	Uniform commercial code carton-label errors
Invoicing	3	2	Invoices included with shipment rather than mailed separately
Overshipped, undershipped, or damaged merchandise	4	0	Unauthorized merchandise substitutions
Pack-by-store	5	5	Incorrect or missing store number on cartons

execution-quality errors that retailers list most often, and we summarize the chargebacks that retailers use in response to these errors. Because each retailer does not necessarily list a penalty for each execution-quality error, the number of observations per error varies.

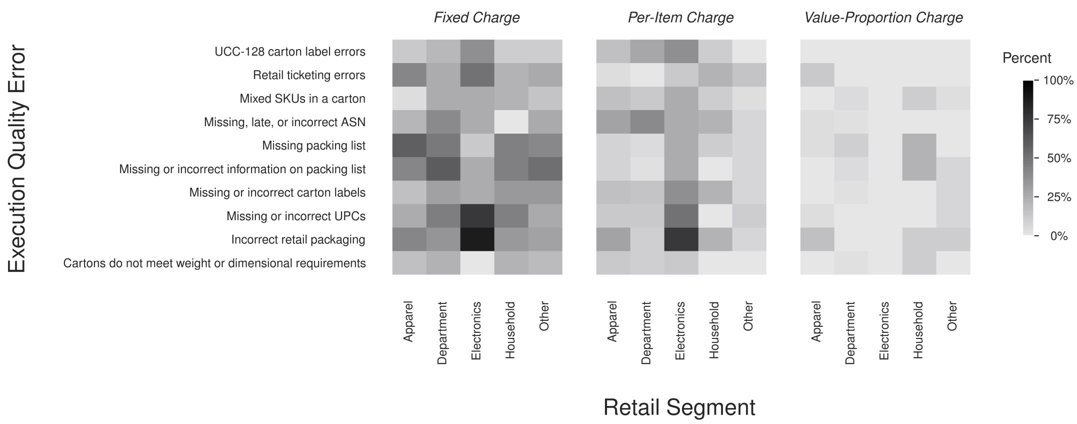
Table 2: Chargeback penalties for specific execution-quality errors.

Execution Quality Error	**Count of Retailers that List Error**	**Fixed Charge**		**Per-Unit Charge**		**Value-Proportion Charge**	
		Count of Retailers	*Mean (S.D.) of Charge ($)*	*Count of Retailers*	*Mean (S.D.) of Charge ($)*	*Count of Retailers*	*Mean (S.D.) of Charge (%)*
Missing or incorrect carton labels	46	46	152.50 (86.19)	3	0.12 (0.26)	12	8.33 (4.51)
Missing or incorrect UPCs	29	29	195.00 (286.15)	22	0.38 (0.64)	1	5.00 (-)
Missing packing list	40	40	155.00 (93.40)	3	0.27 (0.27)	0	-
Retail ticketing errors	27	27	106.82 (97.53)	20	0.60 (0.68)	0	-
UCC carton-label errors	29	29	277.63 (298.36)	20	0.97 (0.17)	0	-

Table 2 demonstrates several patterns. First, retailers generally rely on one or two penalty types when constructing chargebacks for a given fulfillment error. Second, fixed charges are the most common type of penalty. Third, retailers prefer to use charges that scale with the quantity of affected units rather than charges that scale with the value of affected units. Finally, there is a negative correlation (-0.638) between the magnitude of fixed and per-unit charges, suggesting that retailers treat the two charge types as substitutes.

Our analysis of chargeback manuals reveals that only eight of the retailers vary chargeback magnitudes across suppliers or products. These retailers specify charge types (e.g., a fixed charge plus a per-unit charge) and specify that they will set penalty magnitudes on a per-supplier basis. The eight retailers that vary their penalty magnitudes state that magnitudes vary according to channel (e.g., catalog versus store) and product category (e.g., apparel versus household goods).

Figure 1: Retailers' use of fixed, per unit, and value-proportion charges to address execution-quality errors by retail segment.

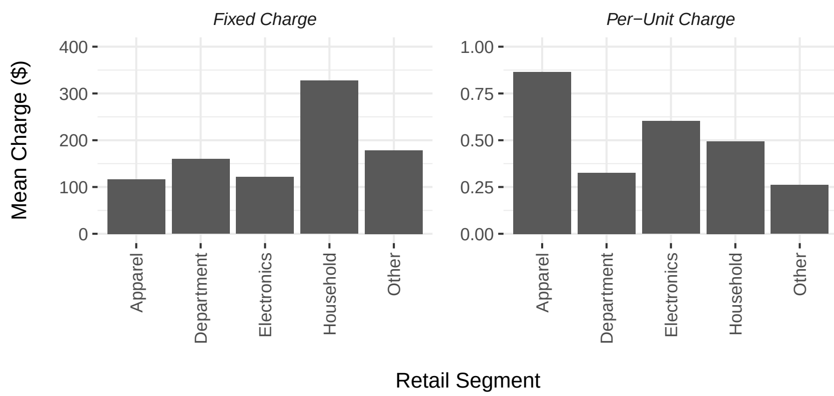


The heat map depicts the percentage of retailers in each segment that use a given charge type to penalize the most common execution-quality errors. The darker squares indicate that a greater percentage of retailers in a segment use a charge type to penalize an error.

We observe variation across retail segments in the types of charges a retailer applies. Figure 1 illustrates the rate at which retailers in different segments use fixed, per unit, and value-proportion charges to address the most common execution-quality errors. We observe that retailers in the electronics segment do not employ the value-proportion charge. Further, no retailer uses the value-proportion charge to address carton-size requirements, missing packing lists, retail ticketing errors, or uniform commercial code (UCC) carton-label errors.

Moreover, there are differences in the magnitude of chargebacks across retail segments. We depict in Figure 2 the mean fixed and per-unit chargeback magnitudes by segment for the chargebacks in Table 2. Figure 2 summarizes differences across segments in the use of chargeback magnitudes. For example, apparel retailers issue the largest per-unit charges on average, whereas household goods retailers issue the largest fixed charges.

Figure 2: Mean fixed and per-unit charges by retail segment.



The majority of the chargebacks and errors listed in the supplier compliance manuals do not address product price, product quality, product quantity, or delivery times. Hence, these chargebacks do not share costs of demand uncertainty or product-quality uncertainty. Rather, the chargebacks establish transfers from suppliers to retailers for lapses in execution quality. In Section 4, we evaluate the ability of the chargeback types we identify from the supplier compliance manuals to communicate the cost of execution quality. In Section 5, we develop a game between a retailer and supplier to assess the extent to which the chargeback types retailers use in practice are able to coordinate a supply chain on execution quality.

4 Inventory Management with Execution-Quality Errors

In this section, we use a standard trade-off model from operations management, the economic order quantity (EOQ) model, to gain insight into how execution-quality errors and chargebacks impact decision making. We extend the EOQ model to incorporate the dependence of execution-quality errors on order quantity as well as the impact of errors on rework costs. We quantify the magnitude of the cost of execution-quality errors in Section 4.1. In Section 4.2, we measure the discrepancy between the cost of execution-quality errors and chargebacks. We conclude that both the cost of errors and the discrepancy between that cost and chargebacks can be substantial and managerially significant. We highlight herein the findings from our model development and analysis, while full details can be found in Appendix A.

As in the traditional EOQ, demand for a product carried by the retailer arrives at a constant rate. The retailer incurs a fixed ordering cost for each PO placed with the supplier, regardless of the order quantity. For each unit of product, there is a constant holding cost per unit of time, which includes capital and storage costs. We assume the retailer receives product at a DC and can backlog demand from stores at a fixed cost per unit of product, per unit of time. We define *execution-quality cost* as the extra cost a retailer incurs due to the presence of execution-quality errors. In the absence of execution-quality errors, the optimal order quantity is the traditional EOQ. In the presence of execution-quality errors, the extra cost a retailer incurs (i.e., execution-quality cost) includes the direct cost of rework—e.g., inspecting unlabeled cartons or fixing incorrect tickets—as well as changes in ordering, holding, and backlogging costs due to execution-quality errors. Hence, the optimal order quantity balances ordering, holding, backlogging, and rework costs.

The retailer detects execution-quality errors as part of the inbound receiving process. For example, when a bar code does not scan, employees recognize immediately that they are unable to process the associated shipment through an automated receiving system. Upon identification of an error, the retailer must correct all items before routing the shipment through normal processes. Hence, when an execution-quality error occurs, we assume the retailer must complete rework on the shipment before using units within the shipment to fulfill demand. Finally, we assume that the retailer does not pay holding cost for products during the rework process. A retailer often pays for a shipment only after completing rework; therefore, the retailer avoids capital cost, a large component of holding cost, for a shipment undergoing rework.

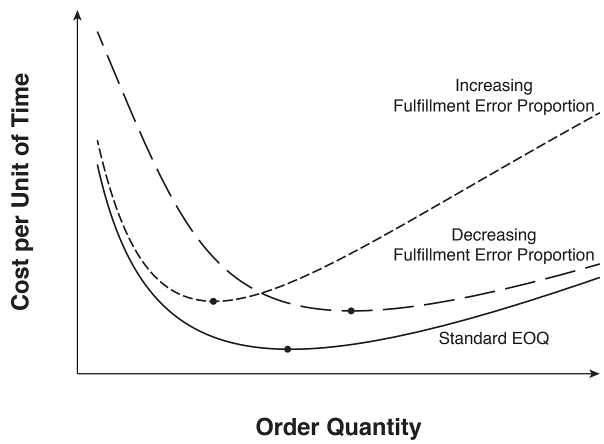
We use the approach of Craig et al. (2015) to model the cost of execution-quality errors to the retailer as a function of the order quantity. The order quantity is not an upper bound on the count of unit-level errors, because a single shipment can experience multiple execution-quality errors in the retail context. For example, a shipment may have both unreadable carton labels and incorrect retail tickets. Suppose a shipment contains five units. The shipment experiences an ASN error, and, further, all five units have incorrect tickets. The count of unit-level errors that require retailer rework for this example is ten.

We assume that the time required to perform rework on a single unit affected by an execution-quality error is a constant. This constant represents the mean rework time in a context where multiple types of errors occur. The retailer pays a cost per unit of time that a shipment is undergoing rework for labor and similar expenses.

The error proportion function determines the relationship between order quantity and the proportion of units that experience errors. We define three general cases for the error proportion function, each with different implications for the optimal order quantity. The error proportion function may be decreasing (Craig et al., 2015), constant (Peters et al., 1988; So and Tang, 1995), or increasing (Porteus, 1986; Lee, 1992) with respect to the order quantity.

The total cost per unit of time for the retailer's inventory system incorporates the rework cost per unit of time alongside the traditional components of the EOQ cost function: setup and holding cost per unit of time (see Equation (A.1) in Appendix A). As previously defined, execution-quality cost is the difference between the optimal system cost with execution-quality errors and the optimal EOQ cost (Equation (A.2)), which is the cost the retailer would realize in the absence of execution-quality errors. Therefore, execution-quality cost is the true cost of errors that retailers incur and could pass on to vendors to align supply-chain incentives.

Figure 3: Cost functions for the standard EOQ and models with execution-quality errors and rework.



The optimal order quantity depends on the relationship between the error proportion and the order quantity. The dot on each cost curve signifies the optimal order quantity. The optimal order quantity for the decreasing error proportion case (i.e., the retail fulfillment context) is less than the EOQ, while the optimal order quantity for the increasing error proportion case (i.e., the production context) is greater than the EOQ. This highlights the importance of characterizing the relationship between errors and order quantity as well as distinguishes between retail and production contexts.

The optimal order quantity depends on the error proportion function. Figure 3 compares the standard EOQ cost function to cost functions assuming a decreasing and increasing error proportion. An increasing (decreasing) fulfillment error proportion reduces (increases) the optimal order quantity relative to the standard EOQ. As discussed in the literature review, a decreasing error proportion rate has been observed in a retail fulfillment context, whereas an increasing error proportion rate has been observed in a manufacturing context. When accounting for the order fulfillment error proportion, the optimal order quantity changes, and the direction of that change depends on the shape of the order fulfillment error function.

4.1 Inventory System Numerical Experiments

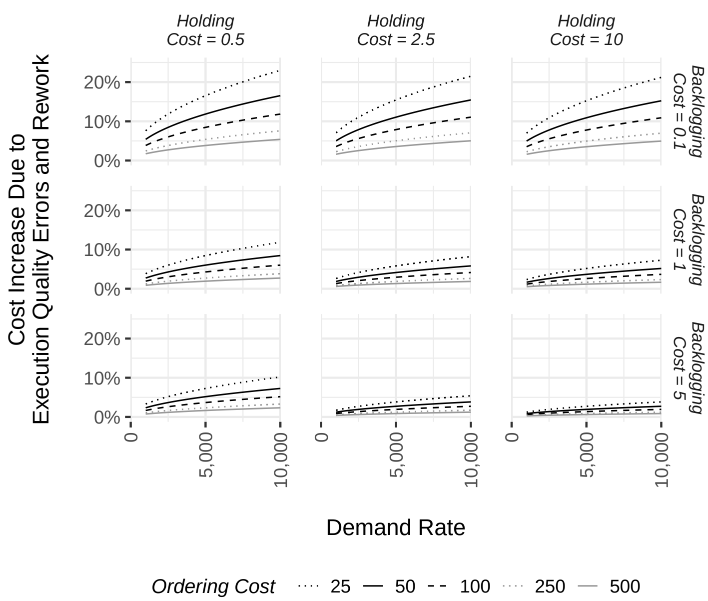
To evaluate the magnitude of the disconnect between chargeback penalties and the cost of execution-quality errors to a retailer, we must characterize the magnitude of execution-quality cost. We rely on parameter ranges derived from empirical research on execution quality (Goh and Sharafali, 2002; Craig et al., 2015). The parameters reflect the variety of products and processes found at a major retailer.

We analyze a total of 16,380 scenarios. The scenarios comprise all combinations of the following parameters. Ordering cost varies from 25 to 500 per order and takes the following values: 25, 50, 100, 250, and 500. Holding cost and backlogging cost may be 0.1, 0.5, 1, 2.5, 5, or 10; the values capture situations wherein the ratio of holding cost to backlogging cost varies from 0.01 to 100. Following Craig et al. (2015), we fix the rework time per unit at 0.1 and the cost of rework per unit of time at 1. Demand varies from 1,000 to 10,000 per unit of time in increments of 100.

To illustrate how the number of units affected by execution-quality errors changes with order quantity, consider the case when the demand rate is 5,000, order cost is 250, holding cost is 0.5, and backlogging cost is 0.1. The EOQ for these parameters is 5,477. If the retailer orders 5,477, then 274 units (5 % of units ordered) will experience an error. If the retailer orders 6,000 units, then 280 units (4.67 % of units ordered) will experience an error. If the retailer decreases its order to 5,000 units, then 268 units (5.35 % of units) will experience an error.

Figure 4 presents, for an illustrative subset of the scenarios we study, execution-quality cost as a percentage of the optimal cost in the absence of errors. Across all scenarios we study, execution-quality cost ranges from 0.01 % to 29.22 % of the optimal cost without errors, suggesting that errors can add substantial cost to inventory systems. We observe that execution-quality cost as a percentage of optimal cost increases with demand rate and decreases with holding cost, backlogging cost, and ordering cost. In

Figure 4: Increases in cost due to execution-quality errors and rework.



The figure depicts how the impact of execution-quality errors on cost changes with the parameters of the EOQ model. Each point on the curves represents the increase in cost due to execution-quality errors and rework for a given combination of the EOQ parameters. The cost increase is relative to the system cost when execution-quality errors are absent. For example, the solid line in the top-left panel depicts the case wherein holding cost is 0.5, backlogging cost is 0.1, and ordering cost is 25. In that case, the increase in cost due to execution-quality errors ranges from 8 % when demand is 1,000 to 23 % when demand is 10,000. The figure demonstrates how execution-quality cost increases with demand rate and decreases with holding cost (e.g., moving right along the columns), backlogging cost (e.g., moving down the rows), and ordering cost.

particular, Figure 4 illustrates the near tenfold increase in execution-quality cost across the range of demand when holding, backlogging, and ordering costs are constant. These results suggest that retailers should pay particular attention to execution-quality errors involving fast-moving products that the retailer orders frequently.

4.2 Chargeback Penalty Numerical Experiments

To assess whether the chargeback penalties retailers use in practice accurately convey the cost of execution-quality errors, we explore the mismatch between chargebacks and execution-quality cost. We model the forms of chargebacks used in practice (see Section 3): a fixed charge, a per-unit charge, and a value-proportion charge. The chargeback penalty function (Equation (A.6)) incorporates charges of all three types and combine them into a penalty per unit of time.

We show, in Appendix A, that a retailer with a chargeback policy that does not change with product characteristics (i.e., demand rate, ordering cost, holding cost, and backlogging cost) and process parameters (i.e., rework cost and time) will undercharge suppliers in some situations and overcharge in others. We define the chargeback gap for a given product to be the chargeback penalty less the true execution-quality cost. A positive chargeback gap occurs when the retailer overcharges the vendor for the execution-quality cost in a particular scenario.

We present in the second column of Table 3 summary statistics of the chargeback gaps for each of three chargeback structures. First, a structure that uses all charge types from Section 3, namely, a fixed charge, per-unit charge, and value-proportion charge. Second, a structure that employs fixed and per-unit charges, which are the two types of charges retailers use most often. Third, a structure with only a fixed charge, which is the single most common type of charge. The latter two structures match many of the actual chargebacks we observe in practice (see Table 2). We measure the chargeback gap by minimizing the absolute deviation of the chargebacks from execution quality across all products.

Table 3: Mean and standard deviation of the absolute chargeback gap for all scenarios as well as subsets defined by a variety of holding costs.

	Scenarios			
Charge Types	All Scenarios (N = 16,380) *Mean (S.D.)*	Holding Cost = 10 (N = 2,730) *Mean (S.D.)*	Holding Cost = 1 (N = 2,730) *Mean (S.D.)*	Holding Cost = 0.1 (N = 2,730) *Mean (S.D.)*
All Types	11.34 (9.08)	11.26 (8.94)	10.69 (8.90)	8.33 (9.76)
Per-Unit and Fixed	20.46 (9.59)	19.01 (9.41)	19.76 (9.55)	19.90 (9.56)
Fixed	22.62 (7.69)	20.01 (8.37)	20.05 (7.94)	20.12 (6.82)

The absolute chargeback gaps are relative to the chargeback policy that minimizes the absolute deviation between execution-quality cost and the chargeback penalties for each set of scenarios. We observe that using all charge types reduces the chargeback gap by approximately 50 % in comparison to using one or two charge types. The reduction in charge types remains pronounced when holding cost is fixed and is largest when holding cost is low.

When the retailer uses all charge types, the mean absolute chargeback gap is 11.34, which is, on average, 37.73 % of execution-quality cost. The chargeback policies that employ one or two charge types, which are the most common approach we observe in the vendor compliance manuals, lead to chargeback gaps that are roughly twice as large as the chargeback gaps of the policy that uses all three charge types. Nonetheless, retailers rarely use all three charge types in practice. The chargeback policy that incorporates fixed and per-unit charges has a mean absolute chargeback gap of 20.46, while the chargeback policy that uses only a fixed charge has a mean absolute chargeback gap of 22.62.

Some of the model parameters may not vary substantially for a given retailer. For instance, a retailer's holding cost may depend primarily on its financial structure. In that case, not all combinations of parameters for the numerical experiments would be relevant for the retailer. Further, the analysis that sets a single chargeback policy across all scenarios might overstate the mismatch between the retailer's execution-quality cost and the corresponding chargeback penalties. The third through fifth columns of Table 3 describe the mismatch for three alternate cases that fix holding cost to high (10), medium (1), and low (0.1) values. We find that a substantial chargeback gap persists for the subsets of parameter values. Overall, we conclude that the difference between execution-quality cost and chargebacks can be managerially significant.

5 The Supplier's Response to Chargeback Penalties

The purpose of chargeback penalties, from the perspective of supply-chain coordination, is to induce the supplier to invest in the optimal level of execution quality for the supply chain. For example, if poor execution quality is expensive for the retailer but inexpensive for the supplier to remedy, then it can be more efficient for the supplier to address execution-quality issues. Large chargebacks that reflect a high cost of inferior execution quality to the retailer should induce the supplier to increase its execution quality when doing so is less expensive than incurring the chargeback. In this section, we study the interplay between the retailer's and supplier's decision regarding chargebacks and execution quality. In practice, the retailer and the supplier jointly determine chargeback penalties and execution quality and aspects of the supply relationship beyond chargebacks can affect the retailer's and supplier's decisions. For instance, a supplier's ability to absorb chargeback penalties may depend on a supplier's profitability. Similarly, the supplier's bargaining power in the channel relative to the retailer's may influence its ability to increase price in response to chargebacks. Overall, supply-chain decision-making depends on this retailer-supplier dynamic. We present herein the insights derived from a model of this dynamic. The full details of our modeling approach can be found in Appendix B.

The analysis incorporates several important factors that affect the use of chargebacks as a mechanism for coordinating execution quality. First, the extent to which the supplier improves its execution quality in anticipation of penalties depends not only on the penalties but also on the cost to the supplier of enhancing execution quality. Second, a powerful supplier may counteract chargebacks with price increases. Both the retailer and the supplier must consider their respective costs of addressing execution quality as well as their abilities to communicate those costs via chargebacks or price changes. Third, the supplier's profitability affects its ability to absorb chargeback penalties: an unprofitable supplier cannot maintain the supply relationship.

The retailer and supplier engage in Stackelberg competition, in which the retailer is the leader, and the supplier is the follower. The retailer leads by setting a chargeback policy at the outset of the game. The supplier follows, responding with a level of execution quality. The retailer and supplier have complete information, and the retailer employs the optimal order quantity given the supplier's choice of execution quality.

The supplier sets execution quality by adjusting the error proportion function, where increasing execution quality leads to fewer errors for a given order quantity. Execution quality is costly to the supplier (see Equation (B.1) in Appendix B), and both the cost and the marginal cost of execution quality to the supplier increase as quality improves. Moreover, the supplier's cost of execution quality increases as the order quantity grows.

Depending on the supplier's power within the relationship, the supplier may increase its price to pass some of the costs associated with managing execution quality back to the retailer. On one extreme, a supplier with no power is unable to pass any cost to the retailer. On the other, a supplier with total power can pass the entire cost of execution quality to the retailer.

The supplier's total cost function per unit time incorporates chargebacks and costs associated with increasing execution quality (Equation (B.3)). The supplier's profitability constrains the magnitude of the retailer's chargebacks. Specifically, a supplier can only participate in the supply relationship when revenues cover costs.

The retailer's cost per unit time incorporates its inventory system cost, revenues from chargebacks, and any costs the supplier is able to impose on the retailer (see Equation (B.4) in Appendix B). The retailer's chargeback penalty may be any of the charges we observe in practice: fixed, per-unit, or value-proportion (Equation (B.2)). The model in Appendix A of the inventory system with rework determines the retailer's inventory cost.

As the retailer increases the level of chargebacks from a level of 0, the supplier initially responds by increasing quality. The supplier thus balances chargeback penalties against its cost of execution quality. When the supplier improves execution quality, the retailer's optimal order increases, and its inventory system cost decreases. The retailer seeks to balance its benefits from chargebacks—i.e., inventory system cost reductions and chargeback revenues—against the drawbacks—i.e., price increases. However, the supplier's profitability bounds the retailer's chargebacks and may prevent the retailer from reaching the unconstrained optimal level of chargebacks.

The best possible performance of the supply chain occurs when the parties coordinate to minimize total cost (Equation (B.5)). Coordination directly balances the benefits of higher execution quality to the retailer against the cost of execution quality to the supplier. The parties might achieve coordination by monetary transfers, e.g., if the retailer were to subsidize the supplier's execution quality capabilities, or by integration.

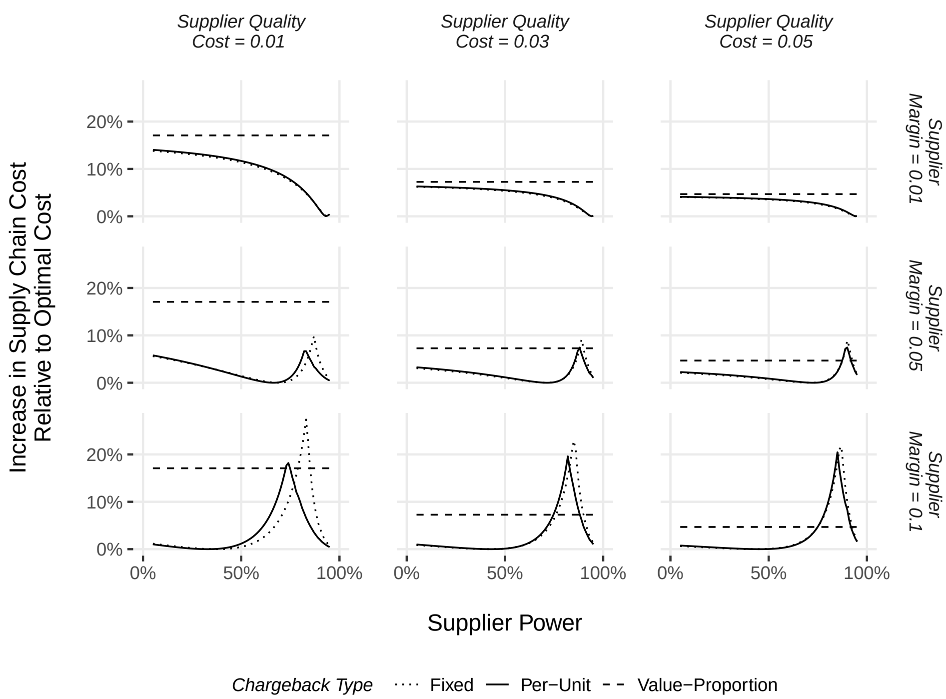
To assess the impact of misaligned incentives on the supply chain's performance, we compare the supply-chain outcome to two benchmarks. The first benchmark is the outcome for the case in which the retailer and the supplier coordinate. Another benchmark for supply-chain performance is the outcome when the supply chain uses no chargeback or penalty mechanisms. In the absence of an incentive to increase execution quality, the supplier will minimize its cost by setting execution quality to the lowest level.

We illustrate the results of the game using numerical experiments that build on the parameter values of Section 4.1. We vary the form of the chargeback penalty, the cost to the retailer of rework, the cost to the supplier of execution quality, the power of the supplier, and the profitability of the supplier. For the retailer's cost of rework, we fix a at 0.1 as before and vary c over $\{1, 2, \ldots, 10\}$. The parameter for the supplier's cost of execution quality (Equation (B.1)) varies over $\{0.01, 0.02, \ldots, 0.1\}$. We employ values of supplier power from 0.05 to 0.95 in increments of 0.05. The supplier's margin may be 0.01, 0.05, 0.1, or 0.2 per unit. Finally, consistent with retailers' practice of using a single charge type, the chargeback penalty function may implement the fixed-charge penalty, the per-unit penalty, or the value-proportion penalty. All combinations of the parameter values yield a total of 373.46M scenarios.

We measure the performance of the supply chain via the increase in cost when the retailer uses chargebacks in comparison to the outcome for the coordinated supply chain that minimizes total cost. To place the cost increase in context, we state the increase as a percentage of the minimum total cost. Across all scenarios, the use of chargebacks increases cost by an average of 18.95 % relative to the minimum total cost. Hence, the parties' inability to coordinate on execution quality can substantially decrease supply-chain performance. Nonetheless, the cost the supply chain experiences in the absence of any chargeback or penalty mechanism is, on average, a 38.49 % increase in cost relative to the minimum total cost. Chargebacks can, therefore, increase the supply chain's performance in comparison to the case wherein the chain uses no coordination mechanisms while leaving substantial opportunity for further improvement.

Figure 5 compares the performance of the different charge types. We observe that no single charge type is universally optimal. The fixed and per-unit charge types vary similarly with order quantity and execution quality. When the supplier's power is low, the supplier's margin limits both the per-unit and fixed charges; hence, those charges

Figure 5: The increase in supply-chain cost relative to the cost under coordination varies with the charge type, the retailer's cost of rework, and the supplier's power and margin.



Each point on the curves represents the increase in cost due to the retailer's and supplier's decisions regarding chargebacks and execution quality, respectively, for a given combination of model parameters. The cost increase is relative to the optimal system cost when the retailer and supplier coordinate on execution quality. In the figure, the demand rate is 5,000, the ordering cost is 100, the holding cost is 0.1, the backlogging cost is 2.5, and the retailer's cost of rework is 1.

induce similar levels of execution quality and overall performance. However, as the supplier's power grows, and when the supplier's margin supports large chargebacks, the per-unit charge can substantially outperform the fixed charge, which varies only indirectly (i.e., via the order quantity) with the supplier's decision.

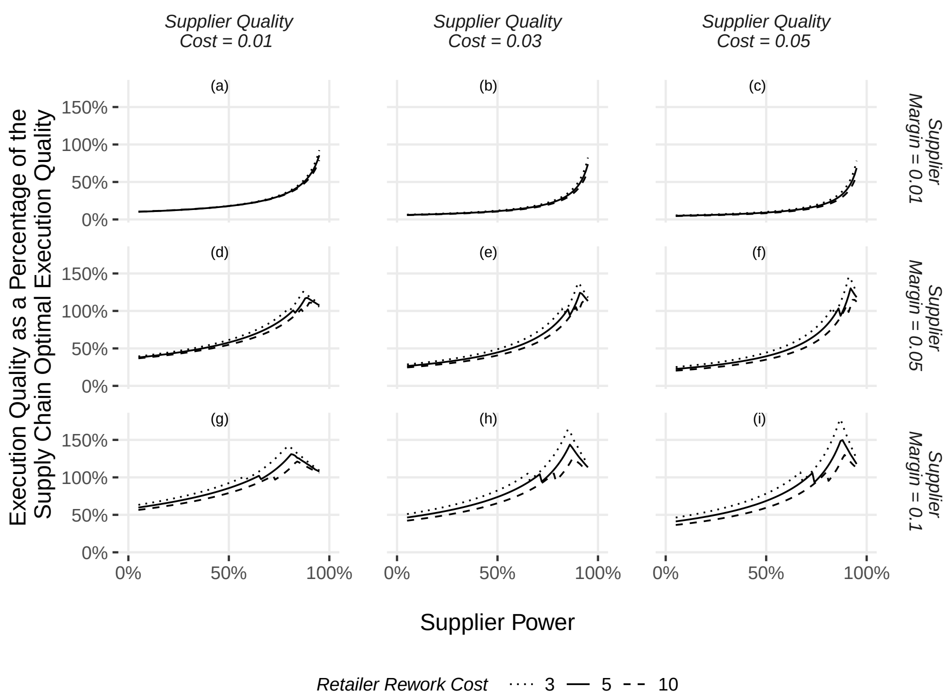
In contrast, the value-proportion charge does not vary with the parties' decisions; hence, the charge simply transfers profit from the supplier to the retailer. Nonetheless, the value-proportion charge can outperform the other charge types by preventing the supplier's over-investment in execution quality when the supplier's margin and quality cost relative to the retailer's cost are both large. In that case, a retailer's fixed or per-unit charge can each drive the supplier's execution quality too high from a supply-chain perspective.

We observe, in Figure 5, that the performance of the supply chain varies across different charge types. The increase in cost relative to the minimum total cost averages 17.01 % for the fixed charge, 12.87 % for the per-unit charge, and 26.96 % for the value-proportion charge. For the remaining analyses, wherein we are not comparing across chargeback types, our approach is to use the charge type that leads to the lowest increase in cost in each scenario. Hence, the analysis is conservative and bounds the performance of the supply chain under chargebacks.

The parties' decisions and the performance of the supply chain vary substantially with the cost to the retailer of rework and with the supplier's power and margin. Figure 6 depicts the supplier's choice of execution quality when the retailer uses the optimal chargeback policy relative to the supply-chain-optimal execution quality. As the figure shows, the supplier's chosen execution quality may under or over-shoot the optimal execution quality.

When the supplier's power is low, the supplier bears much of the cost of chargebacks and execution quality, and it is the supplier's profitability that constrains the retailer's

Figure 6: The difference between the realized and optimal execution qualities varies with the retailer's cost of rework as well as the supplier's power and margin.



Each point on the curves represents the change in execution quality due to the retailer's and supplier's decisions regarding chargebacks and execution quality, respectively, for a given combination of model parameters. The change in execution quality is relative to the optimal execution quality when the retailer and supplier coordinate. In the figure, the demand rate is 5,000, the ordering cost is 100, the holding cost is 0.1, and the backlogging cost is 2.5.

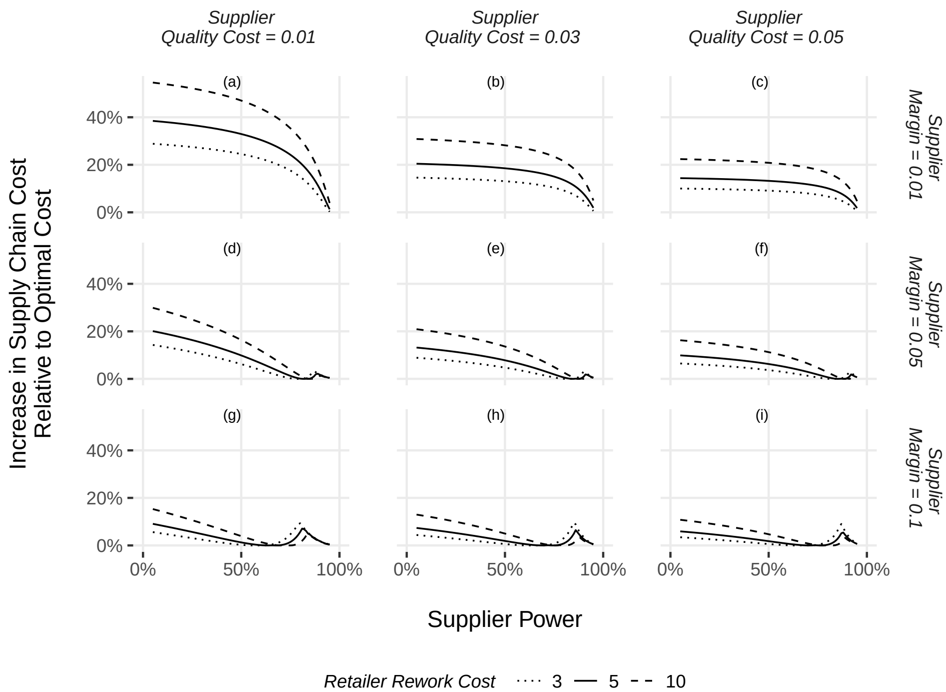
chargebacks. When the supplier's margin is low, the retailer must use smaller chargeback penalties, which can lead the supplier to provide a lower level of execution quality than optimal. As the supplier's margin increases, the retailer can employ larger chargebacks, which push the supplier to an above-optimal level of quality. In general, decreasing the retailer's rework cost reduces the optimal execution-quality level of the supplier, which increases the ratio between the realized execution quality and the optimal execution quality.

Figure 6 shows that, as the supplier's power increases from low levels, the supplier begins to impose the costs of chargebacks and execution quality on the retailer. The supplier's effective cost of execution quality decreases, and the supplier's quality increases relative to the optimal. A small supplier margin constrains the retailer's chargebacks, and increases in the supplier's power thus transfer the cost of execution quality to the retailer. In effect, the retailer subsidizes the supplier's cost of execution quality, particularly when that cost is low, in which case the supplier's execution quality approaches the optimal level.

When dealing with higher-margin suppliers, the retailer uses substantial chargebacks when the supplier's power is low. Such chargebacks can drive execution quality well above the optimal supply-chain quality. When the supplier's power is high, the retailer decreases the magnitude of the chargebacks as the supplier's price increases exceed the benefits of increasing execution quality. Regardless of the supplier's margin, the level of execution quality approaches optimal as the supplier's power approaches the maximum, since the retailer's objective is identical to the system objective when the supplier is able to pass all execution-quality costs to the retailer.

Figure 7 illustrates how the interplay of the supplier's cost of execution quality, the supplier's margin, and the retailer's cost of rework affects the cost of the supply chain. The figure depicts the percentage increase in the supply chain's cost relative to the optimal supply-chain cost. The figure shows the extent to which the sub-optimal levels of execution quality from Figure 6 impose extra costs on the supply chain.

Figure 7: The percentage increase in cost for the supply chain under chargeback penalties in comparison to the cost under coordination varies with the supplier's power and margin.



Each point on the curves represents the increase in cost due to the retailer's and supplier's decisions regarding chargebacks and execution quality, respectively, for a given combination of model parameters. The cost increase is relative to the optimal system cost when the retailer and supplier coordinate on execution quality. In the figure, the demand rate is 5,000, the ordering cost is 100, the holding cost is 0.1, the backlogging cost is 2.5, and the retailer's cost of rework is 3, 5, or 10. We observe that the charge type that leads to the lowest increase in system cost depends upon the supplier's power, margin, and cost of execution quality.

When the supplier's margin is low, increases in the supplier's power allow the supplier to shift the cost of increasing its execution quality to the retailer (see Panels (a) through (c) of Figure 6). The benefit of cost-shifting differs depending on the relative cost of rework and execution quality. Specifically, as the ratio of the retailer's rework cost to the supplier's cost of execution quality increases, the benefits to the supply chain of the cost-shifting also increase (see Panels (a) through (c) of Figure 7). When the retailer's rework cost is high and the cost to the supplier of improving execution quality is low, the supply chain foregoes a substantial cost reduction if it is unable to coordinate on execution quality. Overall, suppliers use their power for coordination in a manner that improves outcomes for both parties.

When the supplier's margin is moderate or high, the relationship between supplier power and execution quality is more nuanced (Panels (d) through (i) of Figure 6). The supplier's margin determines the extent of the retailer's chargebacks when the supplier's power is low. The result may be levels of execution quality that are below optimal (see, e.g., Panels (d) and (g) of Figure 6). As the supplier's power increases, cost-shifting causes execution quality to approach and, ultimately, exceed the optimal level. At the highest levels of supplier power, price increases cause the retailer to reduce its chargebacks, and the supplier's level of execution quality again approaches the optimal level.

The relationship between supplier power and supply-chain performance is also non-monotonic when the supplier's margin is moderate or high (Panels (d) through (i) of Figure 7). Increases in supplier power initially improve supply-chain performance. As supplier power increases to higher levels, supply-chain performance first decreases, due to excessive price increases and cost-shifting. The potential decrease in supply-chain performance is largest when the supplier has a high margin and low cost of execution quality (compare, e.g., Panels (f) and (g) of Figure 7). Supply-chain performance ultimately improves as the supplier's power approaches its highest level, a situation that mimics vertical integration.

6 Summary

The presence of execution-quality errors can be detrimental to supply-chain performance. We demonstrate the importance of accounting for execution-quality errors in supply-chain decision making by tailoring the traditional EOQ model to incorporate execution-quality errors. The optimal order quantity in the presence of errors depends on whether execution-quality errors increase with order quantity, as in a retail context, or decrease with quantity, as in a production context. The result highlights the importance of using appropriate, context-specific assumptions when modeling execution-quality errors.

Focusing on the retail context, we document the use of chargeback penalties that retailers impose on vendors in attempts to offset the cost of execution-quality errors and induce efforts to eliminate such errors. Our analysis of the compliance manuals used by retailers reveals the presence of three types of chargeback penalties: a fixed charge, a charge that varies with order quantity, and a charge that varies with the cost of products in a shipment. The majority of retailers in our study utilize simple chargebacks (e.g., fixed-charge policies), which is consistent with the recommendations found in the retail trade literature, which contends that simple chargebacks improve supplier compliance. Ideally, chargebacks from retailers would motivate suppliers to invest appropriately in execution quality, thus coordinating the supply chain on execution quality.

We find, however, that these chargebacks do not accurately reflect the cost of execution-quality errors. Chargebacks can differ from the cost of execution-quality errors by as much as 75 %. We show that, among the three different charge types, simple chargebacks (e.g., fixed-charge policies) are particularly ineffective at communicating execution quality cost. We suggest an alternative approach, namely, the use of multiple charge types that vary with at least some product and process parameters, such as demand rate and rework cost.

Our analysis also suggests that the effectiveness of chargebacks for coordinating execution quality depends on aspects of the broader supply relationship, including the supplier's pricing power and margin. For instance, chargebacks are most effective when the supplier has moderate margins and high pricing power. Under these conditions, the retailer can issue reasonable chargebacks, limited by the supplier's margins, and the supplier's pricing power allows the parties to share the cost of execution quality. In contrast, when the supplier's margins are thin, the retailer is unable to issue meaningful chargebacks, and the supply chain's execution quality falls below the optimal level of a coordinated supply chain. In that case, the retailer can benefit from proactively subsidizing the supplier's cost of execution quality.

Collectively, these findings suggest there may be opportunities for retailers to tailor their approach to chargebacks not only by product but also by vendor. Chargebacks, as currently used in practice, may be unable to coordinate supply chains around execution quality. We encourage practitioners and academics alike to seek innovation in the design and use of chargebacks and alternate approaches, such as cooperation and subsidies, for execution-quality coordination.

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A Inventory Model Development

In this section, we analyze the impact of a retailer's product and process characteristics on execution-quality cost. Table A.1 summarizes the model notation.

Table A.1: Summary of notation.

Symbol	Definition
Q	Order quantity
λ	Demand rate
K	Fixed ordering cost
$W(Q)$	Number of units affected by an execution-quality error for an order of quantity Q
$\rho(Q)$	Error proportion function for an order of quantity Q
h and π	Holding and backlogging penalty costs per unit time
a	Units of time required to fix a unit affected by an execution-quality error
c	Cost per unit of time for execution-quality error rework
L	Supplier lead time
$C_r(Q)$	Cost function for inventory system with rework
Q_r	Optimal order quantity for inventory system with rework
$C_s(Q)$	Cost function for the standard EOQ model
Q_s	Optimal order quantity for the standard EOQ model

We model execution-quality errors using the method of Craig et al. (2015). The total count of units that any execution-quality error affects is $W(Q)$. The proportion of units that experience an execution-quality error is $\rho(Q) = \frac{W(Q)}{Q}$. With respect to order quantity, the error proportion may be decreasing ($\rho'(Q) < 0$ for all Q), increasing ($\rho'(Q) < 0$ for all Q), or constant. Table A.2 and summarizes the results regarding how the model parameters affect execution-quality cost for each case.

Table A.2: How execution-quality cost varies with the model parameters.

Error Proportion	Ordering Cost	Holding Cost	Backlogging Cost	Demand Rate	Rework Time	Rework Cost
Decreasing	−	+	+	$+^*$	+	+
Increasing	+	−	−	+	+	+
Constant	0	0	0	+	+	+

The starred entry holds for the error proportion function $\rho(Q) = \alpha Q^{\beta}$ with $\alpha > 0$, $\beta \in (-1, 0)$.

The inventory system cost per unit of time is:

$$C_r(Q) = \frac{\lambda K}{Q} + ca\lambda\rho(Q) + \frac{h\pi}{h+\pi}\frac{Q}{2}, \tag{A.1}$$

where $ca\lambda\rho(Q)$ is the cost of rework per unit of time. To ensure that the system cost is convex in the order quantity, we assume that $\rho(Q)$ satisfies $\rho''(Q) \geq -\frac{2K}{caQ^3}$ for all Q.

Let Q_r denote the optimal order quantity that minimizes $C_r(Q)$. Let $C_s(Q) = \frac{\lambda K}{Q} + \frac{h\pi}{h+\pi}\frac{Q}{2}$ be the cost function without rework—i.e., the cost function for the standard EOQ model. Therefore, $C_r(Q) > C_s(Q)$ for strictly positive rework cost and time. We use $Q_s = \sqrt{\frac{2\lambda K(h+\pi)}{h\pi}}$ to refer to the traditional economic order quantity, which minimizes $C_s(Q)$.

We define execution-quality cost as follows:

$$C_r(Q_r) - C_s(Q_s) = \lambda K\left(\frac{1}{Q_r} - \frac{1}{Q_s}\right) + ca\lambda\rho(Q_r) + \frac{h\pi}{2(h+\pi)}(Q_r - Q_s). \tag{A.2}$$

To conduct the numerical experiments of Section 4.1 and Section 4.2, we employ the decreasing error proportion function that Craig et al. (2015) propose:

$$\rho(Q) = \alpha Q^{\beta}. \tag{A.3}$$

We fix β at -0.75, which is consistent with the value that the prior research measures. For each scenario, we choose α such that the error proportion at the EOQ optimal is 0.05 to reflect prior observations that approximately 10 % of purchase orders experience fulfillment errors while approximately half of fulfillment errors are execution-quality errors (Srinivasan et al., 1994). Therefore, we set $\alpha = \frac{0.05}{Q_s^{\beta}}$.

We begin the analysis by determining the relationship between errors and inventory policy, Q_r. The following proposition identifies the relationship between the optimal order quantity with execution-quality errors and the traditional EOQ.

Proposition 1. *The optimal order quantity, Q_r, has the following properties.*

(a) If $\rho'(Q) < 0$, then the optimal order quantity is greater than the EOQ, Q_s.

(b) If $\rho'(Q) > 0$, then $Q_r < Q_s$.

(c) If $\rho'(Q) = 0$, then $Q_r = Q_s$.

Proof. For the decreasing error proportion case, we have $\rho'(Q) < 0$. For any $Q \le Q_s$, $C_r'(Q) = -\frac{\lambda K}{Q^2} + ca\lambda\rho'(Q) + \frac{h\pi}{2(h+\pi)} \le ca\lambda\rho'(Q) < 0$. The first inequality holds because $-\frac{\lambda K}{Q^2}$ increases in Q while, for the standard EOQ, $-\frac{\lambda K}{Q_s^2} + \frac{h\pi}{2(h+\pi)} = 0$. Therefore, $C_r(Q)$ decreases in Q when $Q \le Q_s$. Since Q_r minimizes the convex function $C_r(Q)$, and since $C_r'(Q_s) < 0$, we have $Q_r > Q_s$. A similar proof yields the remaining parts of the proposition. □

The following proposition demonstrates that the influence of the model parameters on the optimal inventory policy depends on the direction of the error proportion function.

Proposition 2. *The optimal order quantity, Q_r, varies with the model parameters as follows.*

(a) Q_r increases with K and λ. Q_r decreases with h and π.

(b) If $\rho'(Q) < 0$, then Q_r increases with a and c. If $\rho'(Q) > 0$, Q_r decreases with a and c. Otherwise, Q_r is constant in a and c.

Proof. The first-order condition for Q_r is

$$C_r'(Q_r) = -\frac{\lambda K}{Q_r^2} + ca\lambda\rho'(Q_r) + \frac{h\pi}{2(h+\pi)} = 0. \tag{A.4}$$

Differentiating both sides of the first-order condition by K yields $\frac{dQ_r}{dK} = \frac{Q_r}{2K+ca\rho''(Q_r)Q_r^3} > 0$, where the inequality holds due to the convexity condition $\rho''(Q) > -\frac{2K}{caQ^3}$. Differentiating the first-order condition by h gives: $\frac{dQ_r}{dh} = -\frac{\pi^2}{(h+\pi)^2}\frac{Q_r^3}{2K+ca\rho''(Q_r)Q_r^3} < 0$. Switching h and π in the derivation of $\frac{dQ_r}{dh}$ yields $\frac{dQ_r}{d\pi} < 0$.

Differentiating the first-order condition by λ yields $\frac{dQ_r}{d\lambda} = \frac{KQ_r - ca\rho'(Q_r)Q_r^3}{\lambda[2K+ca\rho''(Q_r)Q_r^3]}$. The denominator is positive due to the convexity condition. From the first-order condition, we have $KQ_r - ca\rho'(Q_r)Q_r^3 = \frac{Q_r^3}{2\lambda}\frac{h\pi}{h+\pi} > 0$. Therefore, $\frac{dQ_r}{d\lambda} > 0$. Finally, differentiating the first-order condition by c gives $\frac{dQ_r}{dc} = \frac{-a\rho'(Q_r)Q_r^3}{2K+ca\rho''(Q_r)Q_r^3}$. Therefore, $\frac{dQ_r}{dc} > 0$ when $\rho'(Q) < 0$, and $\frac{dQ_r}{dc} < 0$ when $\rho'(Q) > 0$. Further, $\frac{dQ_r}{dc} = 0$ when $\rho'(Q) = 0$. Switching c and a provides the same result for $\frac{dQ_r}{da}$. □

The following proposition characterizes the relationship between execution-quality cost, $C_r(Q_r) - C_s(Q_s)$, and the inventory parameters.

Proposition 3. *Execution-quality cost varies with the inventory cost parameters in the following manner.*

(a) If $\rho'(Q) < 0$, then execution-quality cost, $C_r(Q_r) - C_s(Q_s)$, decreases in K and increases in both h and π.

(b) If $\rho'(Q) > 0$, then execution-quality cost increases in K and decreases in both h and π.

(c) If $\rho'(Q) = 0$, then execution-quality cost does not change with K, h, or π.

Proof. We begin with the fixed ordering cost, K. Since $Q_s = \arg\min_Q C_s(Q)$, we have, by the envelope theorem, $\frac{d}{dK}C_s(Q_s) = \frac{\lambda}{Q_s}$. Similarly, $\frac{d}{dK}C_r(Q_r) = \frac{\lambda}{Q_r}$. The change in execution-quality cost with respect to K is $\frac{d}{dK}C_r(Q_r) - \frac{d}{dK}C_s(Q_s) = \lambda\left(\frac{1}{Q_r} - \frac{1}{Q_s}\right)$. Therefore, by Proposition 1, execution-quality cost is decreasing in K when $\rho'(Q) < 0$, since $Q_r > Q_s$ in that case. By the same reasoning, execution-quality cost is increasing in K when $\rho'(Q) > 0$ and constant with respect to K when $\rho'(Q) = 0$.

For holding cost, the change in cost for the standard EOQ with respect to h is $\frac{d}{dh}C_s(Q_s) = \frac{Q_s}{2}\frac{\pi^2}{(h+\pi)^2}$. Further, $\frac{d}{dh}C_r(Q_r) = \frac{Q_r}{2}\frac{\pi^2}{(h+\pi)^2}$. The change in execution-quality cost with respect to h is $\frac{d}{dh}C_r(Q_r) - \frac{d}{dh}C_s(Q_s) = \frac{\pi^2}{2(h+\pi)^2}(Q_r - Q_s)$. Thus, by Proposition 1, execution-quality cost is increasing in h for $\rho'(Q) < 0$, since $Q_r > Q_s$. Similarly, execution-quality cost is decreasing in h for $\rho'(Q) > 0$ and constant in h when $\rho'(Q) = 0$. The same relationship holds for the backlogging penalty, π. □

We can determine the general relationship between execution-quality cost and demand, λ for the increasing error proportion case. For the decreasing error proportion case, we incorporate an additional assumption. We assume that $\rho(Q) = \alpha Q^{\beta}$ for $\alpha > 0$ and $\beta \in (-1, 0)$. We selected this functional form for its generality and for its fit with empirical observations of fulfillment errors (Craig et al., 2015). The following proposition describes the relationship between execution-quality cost and demand rate.

Proposition 4. *Execution-quality cost varies with the demand rate as follows.*

(a) If $\rho(Q) = \alpha Q^{\beta}$ for $\alpha > 0$ and $\beta \in (-1, 0)$, then execution-quality cost increases in λ.

(b) If $\rho'(Q) \geq 0$, then execution-quality cost increases in λ.

Proof. By the envelope theorem, we have $\frac{d}{d\lambda} C_s(Q_s) = \frac{K}{Q_s}$ and $\frac{d}{d\lambda} C_r(Q_r) = \frac{K}{Q_r} + ca\rho(Q_r)$. Therefore, the change in execution-quality cost with respect to λ is $\frac{d}{d\lambda} C_r(Q_r) - \frac{d}{d\lambda} C_s(Q_s) = \frac{K}{Q_r} + ca\rho(Q_r) - \frac{K}{Q_s}$. Therefore, execution-quality cost is increasing with demand rate when

$$\frac{K}{Q_r} + ca\rho(Q_r) > \frac{K}{Q_s}. \tag{A.5}$$

This condition holds when the error proportion is either increasing in Q or constant in Q, since, by Proposition 1, $Q_s \geq Q_r$ for those cases. The condition may not hold when the error proportion is decreasing in Q. When the condition does not hold, execution-quality cost decreases with the demand rate. We analyze the decreasing error proportion case for one class of error proportion functions: $\rho(Q) = \alpha Q^{\beta}$ for $\alpha > 0$ and $\beta \in (-1, 0)$. Rearranging the first order condition in Equation (A.4) yields $\frac{K}{Q_r} - ca\rho'(Q_r) Q_r = \frac{h\pi}{2\lambda(h+\pi)} Q_r$, where $\rho'(Q_r) Q_r = \beta\rho(Q_r)$. Further, $\frac{K}{Q_r} + ca\rho(Q_r) > \frac{K}{Q_r} - ca\beta\rho(Q_r)$, since $\beta \in (-1, 0)$. Therefore, $\frac{K}{Q_r} + ca\rho(Q_r) > \frac{h\pi}{2\lambda(h+\pi)} Q_r > \frac{h\pi}{2\lambda(h+\pi)} Q_s = \frac{K}{Q_s}$, where the second inequality holds since $Q_r > Q_s$ for the decreasing error proportion function. Thus, the inequality in Equation (A.5) holds, and execution-quality cost is increasing in the demand rate for $\rho(Q) = \alpha Q^{\beta}$ with $\beta \in (-1, 0)$. $\square$

Finally, the rework cost parameters, a and c, do not enter the standard EOQ model. Hence, the change in execution-quality cost is due to the model with execution-quality errors alone. We find that execution-quality cost increases with both the time and cost required to fix a unit affected by an execution-quality error.

Proposition 5. *Execution-quality cost is increasing in both the cost per unit of time for rework, c, and the time required to fix an execution-quality error, a.*

Proof. We have $\frac{d}{dc}C_s(Q_s) = \frac{d}{da}C_s(Q_s) = 0$. By the envelope theorem, the change in execution-quality cost with respect to c is $\frac{d}{dc}C_r(Q_r) = a\lambda\rho(Q_r)$. The change in execution-quality cost with respect to a is $\frac{d}{da}C_r(Q_r) = c\lambda\rho(Q_r)$. Therefore, execution-quality cost is increasing in both a and c. $\square$

To model chargebacks, we assume the probability that at least one unit experiences an execution-quality error is a constant, δ, that does not depend on Q (allowing the probability of an error to depend on the order quantity complicates the analysis but does not change the result). Let θ be the fixed charge for an execution-quality error. Let γ be the per-unit charge for items affected by an error. Let κ be the cost value per unit multiplied by the value-proportion charge, which is a fixed percentage.

The chargeback penalty per unit time is

$$\tau(Q) = \frac{\lambda}{Q}\left[\delta\theta + \delta\kappa Q + \gamma\rho(Q)\,Q\right]. \tag{A.6}$$

We can implement all of the chargebacks from Table 2 using this function. For example, a penalty comprising a fixed charge plus a per-unit charge would have a value-proportion charge, κ, of 0.

Proposition 6. *The chargeback penalty function does not equal execution-quality cost when product and process parameters vary.*

Proof. The chargeback penalty function is $\tau(Q) = \frac{\lambda}{Q}[\delta\theta + \delta\kappa Q + \gamma\rho(Q)Q]$. We show that it is not possible to select chargeback parameters δ, κ, γ, and θ so that $\tau(Q_r)$ equals execution-quality cost as the retailer's rework cost parameter, c, varies. The proofs pertaining to the remaining product and process parameters are similar.

The derivative of the chargeback penalty function with respect to the retailer's rework cost parameter is

$$\begin{aligned}\frac{d}{dc}\tau(Q_r) &= \left[\gamma\lambda\rho'(Q_r) - \frac{\delta\theta\lambda}{Q_r^2}\right]\frac{dQ_r}{dc} \\ &= \left[\frac{\delta\theta}{Q_r^2} - \gamma\rho'(Q_r)\right]\frac{\lambda a\rho'(Q_r)Q_r^3}{2K + ca\rho''(Q_r)Q_r^3}.\end{aligned}$$

The first term—in brackets—is positive when the retailer's error proportion is decreasing, while the second term is negative. In contrast, the derivative of execution-quality cost with respect to the retailer's rework cost parameter is $\frac{d}{dc}C_r(Q_r) = a\lambda\rho(Q_r)$, which is positive. Since the two derivatives differ in sign, it is not possible for the chargeback penalty function to equal the cost of execution quality as the retailer's rework cost parameter varies. □

B Execution-Quality Game

In this section, we analyze the game between the retailer and the supplier, in which the retailer sets a chargeback policy and the supplier responds with a level of execution quality. The supplier determines execution quality by adjusting β for the error proportion function, $\rho(\cdot)$. We modify the notation for the error proportion function in two ways. First, because larger values of β correspond to larger error proportions and, hence, lower execution quality, we represent the supplier's execution quality decision with $\bar{\beta} = 1 - \beta$. Second, we make the dependence of the error proportion function on $\bar{\beta}$ explicit, since it is now the supplier's decision: $\rho\left(\bar{\beta}, Q\right) = \alpha Q^{1-\bar{\beta}}$.

The supplier sets execution quality, $\bar{\beta}$, to a value in the range $[0, 1)$, where an execution quality of 0 represents the base case wherein the supplier exerts no effort toward increasing execution quality. The range of possible values for β ensures a decreasing error proportion function, consistent with the empirically documented observations of the retail context. The supplier's cost of increasing execution quality is

$$g\left(\bar{\beta}, Q\right) = \frac{s}{\alpha} Q \bar{\beta}^2. \tag{B.1}$$

The parameter s scales the magnitude of the supplier's cost function to represent situations wherein execution quality is relatively expensive or inexpensive for the supplier.

The retailer sets a chargeback policy by selecting $\psi \geq 0$ for one of the chargeback penalty functions,

$$\hat{\tau}_j\left(\psi, \bar{\beta}, Q\right) = \psi\lambda \begin{cases} \frac{1}{Q} & j = \text{fixed} \\ \rho\left(\bar{\beta}, Q\right) - \alpha & j = \text{per-unit} \\ 1 & j = \text{value-proportion.} \end{cases} \tag{B.2}$$

The fixed charge is proportional to the count of orders per time period. For the per-unit charge, the chargeback penalty function subtracts α from the error proportion to ensure that the chargeback penalty approaches 0 as the supplier maximizes its execution quality. The value-proportion charge is proportional to demand and, thus, does not vary with the cycle time or the proportion of errors.

The retailer determines its chargeback policy by selecting ψ in anticipation of the supplier's choice of execution quality. We assume that the retailer orders the optimal inventory quantity given the supplier's chosen level of execution quality. The notation $Q_r\left(\bar{\beta}\right)$ for the retailer's optimal order quantity indicates the dependence of the order quantity on the supplier's decision.

We model the supplier's pricing power via the parameter $\epsilon \in [0,1]$. Specifically, the supplier will increase its price to recover a share, ϵ, of the costs of chargebacks and execution quality. A powerful supplier with an ϵ of 1 imposes all costs of chargebacks and execution quality on the retailer. On the other hand, a weak supplier with an ϵ of zero must shoulder all such costs.

The supplier's total cost function per unit time is:

$$S\left(\psi,\bar{\beta},Q_r\left(\bar{\beta}\right)\right) = (1-\epsilon)\left[g\left(\bar{\beta},Q_r\left(\bar{\beta}\right)\right) + \hat{\tau}_j\left(\psi,\bar{\beta},Q_r\left(\bar{\beta}\right)\right)\right]. \tag{B.3}$$

We assume the supplier's margin per unit to be $m > 0$, and its margin per unit of time is $m\lambda$. The supplier will not participate in the relationship when $m\lambda - S\left(\psi,\bar{\beta},Q_r\left(\bar{\beta}\right)\right)$ is negative.

The supplier responds to the retailer's chargeback magnitude, ψ, by selecting $\bar{\beta} \in [0,1)$ to minimize the cost function $S\left(\psi,\bar{\beta},Q_r\left(\bar{\beta}\right)\right)$. Denote the supplier's best response to a chargeback policy, ψ, as $\bar{\beta}^*(\psi)$. The supplier's decision problem is to maximize $S\left(\psi,\bar{\beta}\right)$ for a given value of ψ. The retailer employs the optimal order quantity for the supplier's choice of $\bar{\beta}$. The constraint on Q ensures that the order quantity satisfies the first-order condition for the order quantity from Equation (A.4) (i.e., that the order quantity is optimal given the supplier's chosen level of execution quality). The supplier's problem is

$$\begin{aligned}
\underset{\bar{\beta},Q}{\text{minimize}} \quad & (1-\epsilon)\left[g\left(\bar{\beta},Q\right) + \hat{\tau}_j\left(\psi,\bar{\beta},Q\right)\right] \\
\text{subject to:} \quad & -\frac{\lambda K}{Q} + ca\lambda\alpha\left(1-\bar{\beta}\right)Q^{-\bar{\beta}} + \frac{h\pi}{2(h+\pi)} = 0 \\
& Q > 1, \quad \bar{\beta} \in [0,1).
\end{aligned}$$

Differentiating the inventory condition with respect to $\bar{\beta}$ and Q gives:

$$\frac{d\bar{\beta}}{dQ} = \frac{caQ^{-\bar{\beta}}\alpha\lambda + ca\left(1-\bar{\beta}\right)Q^{-\bar{\beta}}\alpha\lambda\log\left(Q\right)}{Q^3 - ca\left(1-\bar{\beta}\right)\bar{\beta}Q^{\left(-1-\bar{\beta}\right)}\alpha\lambda}.$$

With respect to $\bar{\beta}$ and Q, the chargeback penalty function, $\hat{\tau}_j\left(\psi, \bar{\beta}\right)$, is constant in the value-proportion case. The fixed chargeback penalty is convex in Q for $Q > 0$. The per-unit chargeback penalty is convex when $\rho\left(\cdot\right)$ meets the convexity condition for the retailer's inventory system (see Proposition 1), i.e., when $-\alpha\bar{\beta}\left(1-\bar{\beta}\right)Q^{-1-\beta} > -\frac{2K}{caQ^3}$.

The retailer's cost function is:

$$R\left(\psi, \bar{\beta}, Q_r\left(\bar{\beta}\right)\right) = C_r\left(Q_r\left(\bar{\beta}\right)\right) - \left(1-\epsilon\right)\hat{\tau}_j\left(\psi, \bar{\beta}, Q_r\left(\bar{\beta}\right)\right) + \epsilon g\left(\psi, \bar{\beta}, Q_r\left(\bar{\beta}\right)\right). \quad \text{(B.4)}$$

The retailer's optimal chargeback magnitude, ψ^*, minimizes $R\left(\psi, \bar{\beta}^*\left(\psi\right)\right)$. The objective functions for the retailer and supplier therefore comprise sums of functions that are convex in $\bar{\beta}$ and ψ. The retailer's optimal ψ must occur either at the border values of ψ or on the interior. The border values for ψ are 0 and the value of ψ that makes the supplier's profitability constraint bind.

Finally, the total cost per unit time for a supply chain that coordinates the execution-quality decision is:

$$T\left(\bar{\beta}\right) = C_r\left(Q_r\left(\bar{\beta}\right)\right) + g\left(\bar{\beta}\right). \quad \text{(B.5)}$$