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The impact of supply disruption risk on a retailer's pricing and procurement strategies in the presence of a substitute product

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Abstract

Retailers often experience stockouts when a supplier fails to deliver an order. In this paper, we identify the optimal procurement policy of a multi-product retailer in the presence of possible supply disruptions. Our analysis reveals that, in anticipation of potential supply disruptions, a retailer would typically benefit from ordering more units from a reliable supplier and fewer units from an unreliable one. Furthermore, the total number of units ordered may increase when there is supply disruption risk. As a result, the retailer may overstock some items. However, there are situations in which a retailer would optimally respond to supply uncertainty by consolidating its selling strategy around the unreliable supplier's product. Under such a strategy, we find the surprising result that the retailer reduces the amount it orders from a reliable supplier as an unreliable seller becomes even less reliable. We also explore how supply disruptions can affect a retailer's optimal pricing strategy. We find that under certain conditions, it is beneficial for a retailer to lower its price of a substitute product when one supplier fails to deliver its product. Finally, we find that, on net, consumers may benefit from supply uncertainty even though supply disruptions eliminate access to a desirable product.

Keywords: Supply disruption; Pricing; Procurement; Product substitutability; Supply uncertainty

Introduction

A 2011 survey indicates that 85 percent of all companies have experienced multiple supply disruptions (Veysey 2011). Furthermore, supply disruptions are becoming more ubiquitous (Culp 2013), perhaps being accelerated by climate changes (O'Marah 2015), the trend toward lengthier and more complex supply chains (Culp 2013, City Wire 2015, Rao 2014, Rosenblum 2013), and the emphasis on cost efficiency, which discourages manufacturers from incorporating resiliency into their supply channels (Kumar 2009, Chopra and Sodhi 2014). Supply disruptions frequently result in stockouts, being responsible for approximately one-quarter of stockouts that retailers experience and causing stockouts to occur even in markets where demand is stable and predictable (Kim and Morton 2015, Gruen and Corsten 2002). Approximately eight percent of products at any given time are out-of-stock and consumers face stockouts in about one of every three shopping trips, thus causing retailers approximately $1 T worldwide in lost sales annually (Howland 2018, Gruen and Corsten 2002).

The COVID-19 crisis has made supply disruptions, and the ensuing stockouts, a particularly important and timely research topic (Roggeveen and Sethuraman 2020). Although operations researchers have extensively studied the causes and impact of supply disruptions, we are not aware of previous work in marketing on this important topic. We believe that this is a critical gap in the literature since supply disruptions and the resulting stockouts can dramatically affect a retailer's ability to satisfy customers' needs. Practitioners stress that retailers need to develop strategies for coping with supply disruptions, including implementing category management plans that are robust to situations in which one or more products are out-of-stock and determining which consumer types to prioritize when product scarcities arise (Byrnes and Wass 2020, Omare 2009). Major retailers, such as Walmart and Target, have recently decried poor delivery performance of their suppliers and undertaken initiatives to rectify this problem (Pandolph 2017, Vitasek 2016). In contrast, supply disruptions could create a potential competitive advantage for a retailer. For example, because of its many strong relation-

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ships with a diverse network of suppliers in the home goods and furniture market, Wayfair asserts that supply disruptions simply generate opportunities to sell other suppliers' products (Motley Fool Transcribers 2020).

Our paper contributes to retail practice by identifying selling strategies that are proactive rather than reactive to supply disruptions. Our proposed strategies rely on using multiple products to protect against supply disruptions. Most previous research ignores how the product mix can affect strategies for addressing supply disruptions. For example, a common methodological approach is to utilize a model with a single retailer selling a single product (e.g., Xu and Ye 2013, Guo et al. 2016, Li et al. 2013, Kazaz and Webster 2011, and Chao and Tang 2013). In contrast, the retailer in our model sells two products. This distinction allows us to explore how a retailer can use the pricing and procurement of multiple products (accounting for the substitution patterns induced by such decisions) to mitigate the impact of supply disruptions. Analysis of a multi-product retailer is of substantial practical importance because most retailers sell multiple products within a given product category and thus can obtain revenue from substitute products if another product stocks out.

Our fundamental objective is to enhance understanding of how pricing and procurement strategies can help mitigate the negative impact of supply disruptions on retailers' profit in multi-product environments. Specifically, we seek to answer the following research questions:

1 How does anticipation of potential supply disruptions affect a retailer's optimal procurement strategy when its suppliers offer vertically differentiated products?
2 How do optimal order quantities vary with the probability of a supply disruption?
3 How should a retailer adjust its prices when a supply disruption occurs?
4 How does supply risk and a retailer's response to this risk impact consumers?

Answering the first question is critical for helping retailers operate most profitably when they face uncertain supply. As noted above, retailers are encountering significant and growing threats from supply disruptions. For example, retailers may find that national brands are failing to be consistently delivered or they cannot find highly dependable manufacturers of their private labels. Thus, retailers need to identify an overarching strategy for dealing with unreliable suppliers. For instance, should a retailer risk heavily utilizing an unreliable supplier if that supplier offers a superior product? Our analysis reveals three potentially viable strategies for dealing with an unreliable supplier: Diversification, Hyper-Diversification, and Entrenchment. Diversification is an intuitive strategy in which the retailer mitigates the effects of potential supply disruptions by procuring a larger total amount of inventory and shifts its orders toward a more reliable supplier.[1] We coin the term Hyper-Diversification to describe a second potentially viable strategy, under which the order amounts are so large that the retailer will discard some units (rather than sell them to consumers) if the unreliable supplier successfully delivers its product. This strategy is optimal if unit costs are sufficiently low, thus giving the retailer a strong incentive to maintain high sales even when a supply disruption occurs.

A third strategy, Entrenchment, is optimal when procurement costs are high and the difference in quality across products is relatively small.[2] Under Entrenchment, the retailer addresses supply uncertainty by retreating from the market, i.e., ordering fewer units in total. Surprisingly, this retreat involves consolidation of the retailer's procurement strategy around the unreliable supplier's product. This interesting result can be explained as follows. High procurement costs increase the importance of being able to maintain high prices. In the event that both products are delivered, the retailer can use a high price for the reliable supplier's product to avoid cannibalization of the other product's sales and as a way to make the unreliable supplier's product appear more attractive to consumers, thus enabling the retailer to obtain substantial profit margins for both products. Anticipating that it will charge a high price for the reliable supplier's product, the retailer orders relatively few units of this product in order to avoid excess inventory.

Since the probability of a supply disruption varies across industries and product categories, it is important for a retailer to know how to choose its order quantities and prices depending upon the order fulfillment probability that it actually faces. Therefore, to address the second research question, we examine how the optimal order quantities and prices vary with the probability that an order will be delivered. We find that these relationships critically depend upon which selling strategy the retailer is utilizing. Specifically, as an unreliable supplier becomes even less reliable, the retailer procures fewer units from this supplier under Diversification, but more units under Entrenchment. Furthermore, the retail price of the unreliable supplier's product remains constant as the probability of a supply disruption varies. Moreover, as one supplier becomes less reliable, the retailer should adjust its procurement and pricing

[1] In the Operations Research literature, diversification refers to a manufacturer acquiring the same input from different sources and is synonymous with the term "multiple sourcing" (e.g., Tang and Kouvelis 2011; Li et al. 2013; He et al., 2016). Throughout this paper, we instead use Diversification to refer to a retailer's strategy of rebalancing its order quantities so that its total sales and profit become less dependent on a product that is procured from an unreliable manufacturer.

[2] Various literatures have used the term entrenchment. In economics, entrenchment refers to a situation in which wealth and power is held by a small number of individuals or families (e.g., Morck, Wolfenzon and Yeung 2005). The corporate finance literature uses this term to describe firms where there is one or a very small number of very large shareholders (e.g., Claessens et al. 2002, Yeh and Woidtke 2005). Political entrenchment refers to incumbent politicians implementing policies that damage the very people who brought them in power (Saint-Paul, Ticchi and Vindigni 2016). Inspired by these alternate definitions, in the current paper, entrenchment involves an action that makes the retailer more dependent on a single supplier, namely the unreliable one.

of substitute products. We find that, under Diversification and Hyper-Diversification, in response to greater supply disruption risk, a retailer should order more units from a reliable supplier and lower the prices of that product. Under Entrenchment, the opposite is true, i.e., the retailer should order fewer units from the reliable supplier and charge a higher price for that product.

It is important to recognize that the retailer can only adjust order quantities in response to the *anticipation* of possible supply disruptions, not in response to actual supply realizations. In other words, if a supply disruption prevents delivery of an order, it is not feasible to acquire more inventory immediately due to a non-trivial production and transportation lead time. However, it is typically feasible for a retailer to adjust prices according to product availability. Thus, our third research question involves examining how a retailer should adjust the prices of products that are available when another item in the product mix experiences a supply disruption. We find that when products are vertically differentiated, the retailer should lower the price of the remaining product when the other product is not received. It is interesting and counterintuitive that a retailer would charge lower prices when realized supply is low rather than high. The rationale behind this result is that, when multiple products are available, the retailer can use a high price for one product to shift demand towards the other product. In contrast, when the products have identical quality and thus are differentiated solely on a horizontal dimension, we obtain the more intuitive result that the retailer should increase the price of the remaining product when the other product stocks out. In this case, elimination of one purchase option creates a higher willingness-to-pay for the remaining product.

Supply disruptions not only undermine retailer profitability, they can also negatively affect consumers. Customers may become disappointed when the retailer is out of stock of their preferred product. Thus, it is important for retailers to understand how supply uncertainty, as well as their own actions for addressing this uncertainty, affects consumer welfare. Clearly, supply disruptions can limit the choice set of consumers, and thus undermine consumer welfare. We find that adoption of the Entrenchment strategy can further harm consumers because this strategy involves reducing total order quantities and raising prices, which makes consumers worse off even when a supply disruption does not actually occur. However, if a retailer adopts Diversification or Hyper-Diversification, as one supplier becomes less reliable, the retailer orders more units from the other supplier and reduces the price of that product. Lower prices generate more surplus for consumers and higher order quantities facilitate a greater number of welfare-enhancing transactions. Interestingly, we find that the benefits that accrue for the alternative product can be so large that a higher probability of a supply disruption can make consumers, as a whole, better off. It is important and counterintuitive that consumers may prefer an environment in which supply is unreliable rather than perfectly reliable. We find that an increase in consumer welfare is possible in a variety of market settings.

In the next section, we review the related literature. In Section 3, we introduce and analyze our focal model of a retailer who sells vertically differentiated products. In Section 4, we examine alternate market characteristics to uncover additional insights about how supply disruption risk affects a retailer who sells horizontally differentiated products and when the retailer faces competition. Section 5 reports the impact of incorporating additional features of supply disruptions, namely penalties for failed delivery and the possibility of partial shipments of the ordered quantity. In Section 6, we conclude with a discussion of managerial implications and potential directions for future research.

Literature review

The current paper resides on the interface of retailing, marketing, and operations research, and thus contributes to the literature in each of these fields. As Kozlenkova et al. (2015) note, there is a tremendous opportunity to make fruitful advances in research by examining a variety of traditionally supply-chain-management topics from the perspective of other fields, such as retailing. In the current paper, we take a step in this direction by bridging the literature on supply uncertainty (which primarily appears in operations management journals) with the literatures on stock-outs and channel coordination (which primarily appear in retailing and marketing journals).

Stockouts

Stockouts may arise when a retailer does not receive merchandise from their suppliers in full and in a timely manner. It has been well established that stockouts can result in customer dissatisfaction and reduce future visits to a store (e.g., Anderson, Fitzsimons, and Simester 2006; Pizzi and Scarpi, 2013; and Sloot, Verhoef and Franses 2005). Stockouts also make it more challenging for retailers to determine the true demand for their products because they do not observe how many consumers altered their purchase decisions due to encountering a stockout (Anupindi, Dada, and Gupta 1998). Because of these negative consequences from stockouts, retailers may be able to attract more customers by reducing stockout frequencies or by offering in-stock guarantees (Grewal et al. 2012). In contrast, Balachander and Farquhar (1994) show that a retailer may benefit from allowing occasional stockouts in order to reduce the extent of price competition with a rival retailer.

The extant literature has identified a variety of mechanisms for reducing the negative impact of stockouts. Several remedies include properly timed and worded communications from the firm (Pizzi and Scarpi 2013), service recovery efforts, such as backorders (Dong et al. 2015), and suggesting a substitute item (Breugelmans, Campo, and Gijsbrechts 2006). In regards to this third option, Messinger and Li (2009) go as far as to suggest that stockouts not only induce sales of substitutes but can even increase consumers' valuations for substitutes. This surprising positive effect arises because soldout products can signal to consumers that demand is high for a product and thus enhance the perceived attractiveness of other, similar products. However, Breugelmans, Campo, and Gijsbrechts (2006) caution that consumers become suspicious if the replacement item has a higher price than the original item. This finding implies that it is not sufficient only to suggest a possible replacement, but the retailer must actually offer alternative purchase options that are attractive to consumers. The current paper builds upon this idea by utilizing a model where the demand for each product shifts depending on whether a substitute product is also available and prices endogenously determine the quantity demanded of each product. Thus, we provide guidance as to how retailers can adopt procurement and pricing strategies that can limit the negative effect of stockouts that are caused by the unreliability of suppliers.

Channel coordination

By analyzing a model in which a retailer decides upon prices as well as how many units of product to order from each manufacturer, our paper builds upon and contributes to previous work that studies channel relationships and the interrelationships between pricing and production decisions. See Niu (2008) for a thorough review of this extensive literature. A key insight from the literature is that one should optimize pricing, inventory and production decisions in an integrated fashion rather than treating each decision separately. Thus, the separation of pricing and operations teams (either within a retailer or across channel members) leads to suboptimal outcomes. The extant literature has accounted for many factors that impact the interaction between pricing and inventory decisions, including channel structure, various coordination mechanisms (such as quantity discounts and franchise fees), demand uncertainty, competition, risk aversion, revenue management, promotional activities, ordering costs, delivery time, purchasing costs, and inventory holding costs). We contribute to this literature by focusing on the factor of supply uncertainty, using a model in which a retailer integrates its pricing and procurement strategies in order to maximize profit. The evidence provided in the Introduction indicates that it is important to study the interactions of supply disruptions and selling strategies because supply disruptions are relatively common and can have a profound impact on retailers' profit.

Supply uncertainty in operations research

There is a vast literature on supply uncertainty in which researchers provide insights about how firms can address (1) uncertainty in the production of outputs and (2) uncertainty in the acquisition of inputs. Researchers consistently find that manufacturers earn less profit when their yield rates are lower or more variable (Xu and Ye 2013, He 2013, Cho and Tang 2013). However, there are diverse findings regarding how a manufacturer can best respond to uncertainty in its production output. He (2013) and Xu and Ye (2013) conclude that manufacturers should set higher prices when there is greater supply uncertainty. In contrast, Cho and Tang (2013) show that supply uncertainty induces a manufacturer to set lower wholesale prices because supply uncertainty shifts channel power away from the manufacturer and towards the retailer. Researchers have also found that supply uncertainty has an ambiguous effect on targeted output levels. For example, Xu and Ye (2013) find that, for a manufacturer who produces in-house, greater yield variability and lower yield rates can either increase or decrease the optimal order quantities. This is consistent with Kazaz and Webster (2011), who find that, in an agricultural market, uncertain yield can have an ambiguous effect on how many inputs (e.g., acreage) a risk-averse producer should acquire. Similarly, He (2013) finds that random yields usually cause a manufacturer to attempt to produce higher quantities, but that, when yield risk is large, quantities decline as supply risk increases.

There is also extensive research regarding how firms can best respond to uncertainty in the acquisition of inputs. The insights from this literature provide guidance for retailers as they develop strategies for procuring a product from a manufacturer who is unreliable and for manufacturers who rely on suppliers to deliver raw materials or component parts. Responsive pricing and utilizing backup suppliers are two common approaches researchers advocate for dealing with uncertain supply of needed inputs. For example, advocates of responsive pricing include Tang and Yin (2007) and Tang, Nurmaya Musa and Li (2012), who demonstrate that a retailer benefits from having the flexibility to price after its supplier's production yield has been realized. This accords with the finding in He (2013) that yield risk has a smaller impact on profit when the firm utilizes responsive pricing. In accordance with these findings, we allow the retailer in our model to defer setting prices until after product delivery.

The second approach of utilizing backup suppliers is based on the idea that multiple suppliers may be able to provide the same (or extremely similar) input but may differ in prices and/or reliability. Intuitively, Li et al. (2014) demonstrates that a manufacturer has an incentive to utilize the lowest cost supplier, but may also procure inputs from a second, higher-cost supplier to reduce its risk (if the risk reduction is large enough to offset the cost difference). Guo, Zhao and Xu (2016) stresses that the optimal procurement strategy depends upon the source of supply uncertainty. Specifically, when supply risk is primarily due to supply disruptions (rather than due to random yields), a manufacturer should order more from the regular supplier and reserve less capacity from the backup supplier. Hou et al. (2012) identifies additional factors that determine the optimal response to a supply disruption, showing that a manufacturer should use a backup supplier when down-time is costly, it is expensive to ramp up production above normal operating levels, and disruption lasts an intermediate amount of time. Our paper also focuses on supply risk that is caused by supply disruptions. However, unlike the aforementioned papers, we do not assume that the suppliers produce perfect substitutes. In our model, the key decision-maker is a retailer, rather than a manufacturer, who sells the supplier's products as distinct brands within its product mix, where the brands differ in quality and thus are viewed as imperfect substitutes by consumers.

It is important to note that all papers mentioned in the previous three paragraphs assume a single retailer sells a single product, as is typical in these strands of research. To the best of our knowledge, there are only two exceptions in the operations research literature that consider the impact of supply disruptions in a setting with multiple products. In He, He and Yuan (2016), two retailers sell a single product that can be procured from two different suppliers. A key finding is that the Nash Equilibrium usually involves both retailers adopting the same procurement strategy, i.e., both use a higher-cost emergency supplier or both do not. In contrast, our model of a multi-product retailer allows us to explore how a retailer can mitigate the impact of supply disruptions by appropriately managing the prices and order quantities of its product mix. In so doing, our approach enables us to provide insights regarding how supply uncertainty for one product can affect procurement and pricing decisions of another, different product. Gupta and Ivanov (2020) shares more similarities with our paper. That paper models a retailer who offers horizontally differentiated products that are procured from two different suppliers, focusing upon how supply reliability affects competition between the suppliers in setting wholesale prices. The key insight is that the reduced reliability for one supplier results in a lower equilibrium wholesale price for that supplier but a higher equilibrium wholesale price for its rival. We incorporate this finding into our model by assuming the less reliable supplier offers a lower wholesale price to the retailer if products are horizontally differentiated. Furthermore, our paper focuses on vertically differentiated products rather than horizontally differentiated ones and examines the effect of supply disruptions, which can result in one product stocking out, rather than random yield, which is the source of supply uncertainty in Gupta and Ivanov (2020).

Model

Modeling assumptions

Supply model

A retailer sells two products, j = L, H. Each product is procured from a different supplier. For convenience, we assume Supplier H manufactures Product H and Supplier L manufactures Product L. Product L has a unit cost of c where $0 < c < 1$. Product H has a higher quality than Product L, where δ represents the quality difference between L and H ($0 < \delta < 1$). Product H has a unit cost of $c + \gamma$ where $\gamma > 0$. We assume $\gamma < \delta$ to ensure that Product H is a viable product offering. The retailer decides how many units (Q_L, Q_H) of each product to order and then determines the prices (P_L, P_H) after delivery. For our focal model, we assume Supplier L is perfectly reliable, whereas Supplier H is not. Specifically, Supplier H delivers the entire order quantity (Q_H) with probability ρ and delivers nothing with probability $1 - \rho$. We assume that a supplier refunds the retailer's entire payment if it is unable to deliver the order. There is no salvage value for unsold units.

The underlying motivation for this focal model of supply uncertainty is that higher quality products are more difficult to manufacture, e.g., require inputs with greater complexity or scarcity, and thus are more likely to experience a supply disruption than lower-quality products. In Section 3.4, we consider an alternate version of the model in which the supply of Product L (rather than Product H) is unreliable. Furthermore, in Section 4, we consider extensions of the model in which supply disruptions may result in partial delivery and penalties paid by the supplier to the retailer.

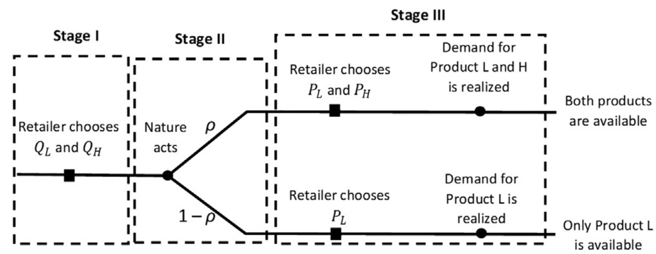


Fig. 1. Decision Sequence.

The sequence of decisions is as follows:

I The retailer orders Q_L units from Supplier L and Q_H units from Supplier H.
II Nature determines whether Product H is delivered.
III The retailer sets the prices for the products that are delivered. Specifically, if both products are delivered, the retailer sets prices P_{Hf} and P_{Lf} for Products H and L, respectively. If only Product L is delivered, the retailer set a price of P_{Ln} for this product.

Fig. 1 provides a graphical illustration of the decision-making sequence.

Demand model

We utilize a linear model of demand. Specifically, when both products are fully delivered and are available for sale (at prices P_{Hf} and P_{Lf}), demand is given by:

$$D_{Hf}\left(P_{Hf}, P_{Lf}\right) = \frac{1}{2}\left(1 - \frac{P_{Hf} - P_{Lf}}{\delta}\right) \tag{1}$$

$$D_{Lf}\left(P_{Hf}, P_{Lf}\right) = \frac{1}{2}\left(1 - P_{Lf} + \frac{P_{Hf} - P_{Lf}}{\delta}\right) \tag{2}$$

This demand specification follows Sayman, Hoch and Raju (2002), with adjustments made to account for the products being vertically differentiated. There are several important characteristics of these demand functions. First, total demand in the market equals one if prices were set to zero, i.e., $D_{Hf}(0, 0) + D_{Lf}(0, 0) = 1$. This implies that the market is not fully covered when prices are positive. Second, holding prices equal, demand for the higher quality product exceeds that of the lower quality one, i.e., $D_{Hf}(P, P) > D_{Lf}(P, P)$. Third, a larger quality difference reduces competition between the products, i.e., $\frac{\partial^2 D_{Hf}(P_{Hf}, P_{Lf})}{\partial P_{Lf}\, \partial \delta} = \frac{\partial^2 D_{Lf}(P_{Hf}, P_{Lf})}{\partial P_{Hf}\, \partial \delta} = -\frac{1}{2\delta^2} < 0$.

If only Product L is available, the demand for Product L is:

$$D_{Ln}(P_{Ln}) = 1 - P_{Ln} \tag{3}$$

As was the case when there was not a supply disruption, a price of zero (for the non-disrupted product) will result in a total demand of one ($D_{Ln}(0) = 1$).

For convenience, Table 1 summarizes the variables of our analytical model.

Table 1
Parameters and Decision Variables.

Variable	Definition
D_H	Demand for the higher-quality product
D_L	Demand for the lower-quality product
P_{Hf}	Price of the higher-quality product (only valid if there is not a supply disruption)
P_{Lf}	Price of the lower-quality product when both products are delivered
P_{Ln}	Price of the lower-quality product when only Product L is delivered
δ	Quality difference between the higher- and the lower-quality products; $0 < \delta < 1$
c	Acquisition cost of the lower-quality product; $0 < c < 1$
γ	Cost difference between the higher- and the lower-quality products; $0 < \gamma < \delta$
Q_H	Retailer's order for the higher-quality product
Q_L	Retailer's order for the lower-quality product
ρ	Probability that the entire order will be delivered

Analysis of pricing and procurement decisions

We solve the retailer's problem using backward induction. In particular, beginning with Stage III, we derive the prices that maximize profit, given order quantities Q_L and Q_H for each possible outcome. Then, moving to Stage I, we derive the order quantities that maximize the retailer's expected profit.

We begin by examining Stage III pricing decisions. Since the retailer can achieve a desired level of sales by choosing prices appropriately, its profit-maximization problem with prices as the choice variables is equivalent to the problem of selecting sales qualities. Because the latter optimization problem is easier to analyze, we derive the inverse demand functions and solve for the realized sales levels that maximize profit.

Suppose the retailer ordered Q_L units of Product L and Q_H units of Product H in Stage I. As a result of Stage II, one of two situations will have been realized: either both products will have been delivered or only Product L will have been delivered. Suppose that only Product L was delivered, i.e., Supplier H experienced a supply disruption. Using Eq. (3), we can derive the inverse demand function:

$$P_{Ln}(D_{Ln}) = 1 - D_{Ln} \tag{4}$$

The retailer's objective is to choose D_{Ln} to maximize the profit in this case (which is equivalent to maximizing the profit by setting P_{Ln}):

$$\pi_n(D_{Ln}Q_L) = P_{Ln}(D_{Ln})\,\mathrm{Min}\,[D_{Ln}, Q_L] - cQ_L \tag{5}$$

The profit-maximizing level of induced demand is:

$$D^*_{Ln} = \mathrm{Min}\left[Q_L, \frac{1}{2}\right] \tag{6}$$

Now consider the outcome in which both products are delivered. Using Eq.s (1) and (2), we can derive the inverse demand functions:

$$P_{Hf}\left(D_{Hf}, D_{Lf}\right) = 2 - 2D_{Lf} + \delta - 2D_{Hf}(1+\delta) \tag{7}$$

$$P_{Lf}\left(D_{Hf}, D_{Lf}\right) = 2(1 - D_{Hf} - D_{Lf}) \tag{8}$$

The retailer chooses P_{Hf} and P_{Lf}, or equivalently, D_{Hf} and D_{Lf} to maximize the profit:

$$\pi_f\left(D_{Hf}, D_{Lf}Q_H, Q_L\right) = P_{Hf}\left(D_{Hf}, D_{Lf}\right)\mathrm{Min}\left[D_{Hf}, Q_H\right] + P_{Lf}\left(D_{Hf}, D_{Lf}\right)\mathrm{Min}\left[D_{Lf}, Q_L\right] - (c+\gamma)Q_H - cQ_L \tag{9}$$

The profit-maximizing level of induced demand is:

$$D^*_{Hf} = \mathrm{Min}\left[Q_H, \mathrm{Max}\left[\frac{1}{4}, \frac{2+\delta-4Q_L}{4(1+\delta)}\right]\right] \tag{10}$$

$$D^*_{Lf} = \mathrm{Min}\left[Q_L, \mathrm{Max}\left[\frac{1}{4}, \frac{1}{2} - Q_H\right]\right] \tag{11}$$

Using these solutions for the Stage III outcomes, we can now derive the optimal order quantities in Stage I. Let $\pi^*_n(Q_L)$ be the optimal profit that can be obtained in the outcome in which supply of Product H was disrupted. This is derived by substituting the optimal induced demand given in Eq. (6) into Eq. (5). Similarly, let $\pi^*_f(Q_H, Q_L)$ be the optimal profit that can be obtained when there is not a supply disruption, which can be derived by substituting the optimal induced demand given in Eq.s (10) and (11) into Eq. (9). The retailer's expected profit is:

$$\Pi(Q_H, Q_L) = \rho\pi^*_f(Q_H, Q_L) + (1-\rho)\pi^*_n(Q_L) \tag{12}$$

Results for focal model

In the Web Appendix, Lemma 1 provides the optimal order quantities, denoted $\left(Q^*_H, Q^*_L\right)$, and the details of optimal price and demand derivations. The Web Appendix also contains proofs of our propositions. Proposition 1 reports our key insights regarding the retailer's optimal strategy and how it depends on the presence of supply disruption risk.

Proposition 1 (Focal Model) *When the supplier of the higher-quality product is unreliable,*

(a) *The retailer reduces the price for the lower-quality product when a supply disruption occurs.*
(b) *The optimal response to the possibility of a supply disruption is to either:*
    order fewer units of the higher-quality product and more units of the lower-quality product, so that the total number of units across both products increases; Or,
    order more units of the higher-quality product and fewer units of the lower-quality product, so that the total number of units across both products decreases.

Optimal pricing

Supply disruption risk creates a challenge to the retailer because the retailer is unable to tailor order quantities to supply realizations. However, the retailer is able to adjust prices according to product availability.[3] Specifically, Proposition 1(a) indicates that the retailer will charge a lower price for Product L when a disruption to the supply of Product H occurs. It is interesting and counterintuitive that a retailer charges lower prices when realized supply is low rather than high. Two factors induce the retailer to reduce Product L's price in response to a supply disruption. First, note that Products L and H are substitutes. Thus, when both products are available, the retailer has an incentive to charge a relatively high price for Product L in order to shift demand for Product H upward, thus allowing any given amount of Product H to be sold at a higher price. When Product H is not available, this demand-shifting effect is absent and thus the firm has an incentive to charge a lower price for Product L relative to the case when both products are available. Second, the retailer may charge a lower price for Product L in order to attract a larger number of consumers. This second rationale for reducing price only arises if there is excess supply of Product L when both products are delivered. If there is no unsold units of Product L when both products are available, then there will not be an expansion effect. We will soon discuss the conditions for which such excess supply may occur.

Optimal procurement strategy

Proposition 1(b) summarizes how the retailer adjusts its order quantities in response to potential supply disruptions. Comparing the optimal order quantities when both suppliers are perfectly reliable to the optimal order quantities when Supplier H is unreliable, we find the retailer may either increase or decrease the order amount of Product L. Specifically, one of the following three strategies will be optimal: Diversification, Hyper-Diversification, or Entrenchment. Table 2 summarizes the key characteristics of each of these three strategies.

In order to facilitate understanding of the required conditions given in the first row of Table 2, Fig. 2 provides an illustration of the parameter regions for which each of the three selling strategies is optimal. In general, we find that Diversification is optimal for a wide range of parameter values, which accords with conventional wisdom regarding how retailers should address supply uncertainty. Under Diversification, the retailer responds to potential supply disruptions by ordering fewer units from the unreliable supplier (H). Because the products are partial substitutes, the retailer can mitigate the loss of profit on Product H sales by increasing sales of Product L. Using the parameter values of $\delta = 0.2$, $\gamma = 0.02$, and $c = 0.08$, Fig. 3(a) shows how order quantities vary with the reliability of Supplier H. In this figure, Diversification is the optimal strategy if $\rho \geq 0.68$. Notice that, as Supplier H becomes less reliable (i.e., ρ decreases from 1), the retailer orders fewer units of Product H and more units of Product L. In order to sell these additional units of Product L, the retailer reduces the price of this product. Fig. 4(a) uses the parameter values of $\delta = 0.2$ and $\gamma = 0.02$ to illustrate how the prices depend on the reliability of Supplier H.

Interestingly, Table 2 and Fig. 3(a) show that under Diversification the total order amount across both products increases as supply disruptions become more likely. Thus, the order amount of Product L increases by more than the order amount of Product H falls. Notice that one factor that limits the order amount of Product L is that it competes for sales with Product H. The retailer has an incentive to reduce such cannibalization. However, as Supplier H becomes less reliable, it becomes less likely that both products will be available in the marketplace and thus less need to reduce order amounts to avoid cannibalization.

Table 2 indicates that another possibly optimal strategy for the retailer is Hyper-Diversification. The distinct feature of Hyper-Diversification is that the total order amounts are so large that some units will go unsold if there is not a supply disruption. Under this strategy, the retailer places larger orders of both products than it would under Diversification, using these larger orders to protect against possible supply disruptions. Fig. 2(a) shows that Hyper-Diversification will be the optimal strategy if unit costs are sufficiently small. When costs are small, overstocking is less detrimental to profit. Furthermore, Fig. 3(a) indicates that Hyper-Diversification arises only when Supplier H is sufficiently unreliable (i.e., ρ is small). When Supplier H is likely to experience a supply disruption, overstocking is less likely to occur because excess inventory only arises when both products are delivered. In a market setting with low costs for Product L and low reliability of Supplier H, the retailer takes the chance of ordering many units of Product L in order to best capitalize on the likely scenario that this will be the only product that it can make available to consumers. As illustrated in Fig. 4(a), the retailer will need to charge a relatively low price in order to sell the large number of units that it has on hand.

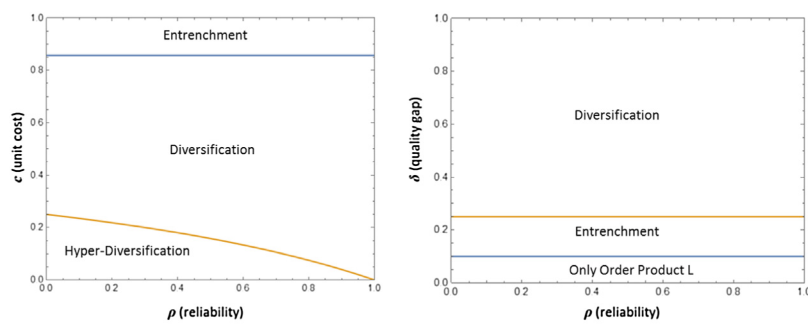
A third strategy, which we refer to as Entrenchment, can be optimal in certain situations. As indicated in Table 2, under Entrenchment, when a product becomes more likely to experience a supply disruption, the retailer orders more units of that product and less of the other (completely reliable) product. This is a quite interesting and counterintuitive response to supply uncertainty. Notice from Fig. 2(a) that Entrenchment is optimal when unit costs are sufficiently large. The combination of high procurement costs and the possibility of supply disruptions makes the market relatively unattractive. The retailer chooses to retreat in the face of such adverse circumstances, reducing its total order amount as the possibility of a supply disruption increases. In this retreat, the retailer consolidates its selling strategy around Product H, with Product L essentially playing the role of a decoy. Since Product L and H are substitutes, demand for H is increasing in the price of L. The retailer utilizes a relatively high price for Product L to enable it to charge an even higher price for the higher-quality product. As a result of the high price of L, the retailer orders few units of L. Notice from Fig. 2(b) that Entrenchment is only optimal when the quality difference between Product L and Product H is small. In such a scenario, the products are close substitutes, which implies that utilizing the decoy effect via Entrenchment can be effective.

[3] In our working paper, we examine an alternative timing in which prices are set prior to observing the supply realizations. If operating expenses are independent of the timing of pricing decisions, then it is strictly more profitable for the retailer to set prices after, rather than before, observing the supply realizations.

Table 2
Optimal Selling Strategy in Response to Potential Supply Disruptions for Product H.

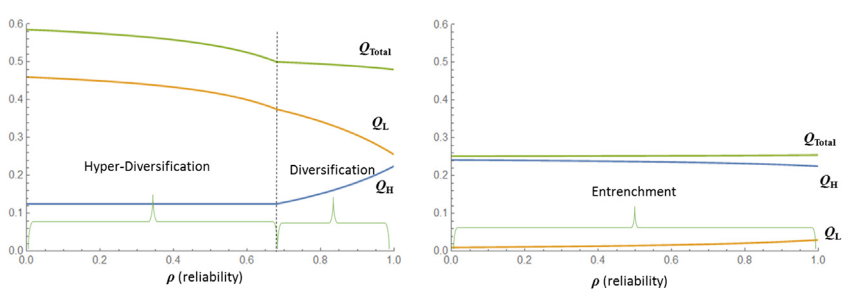
Strategy	*Hyper-Diversification*	*Entrenchment*	*Diversification*
Optimality Conditions	$\delta > c+\gamma$ & $\rho < \hat{\rho}$	$\delta <$ Min $\left[c+\gamma, \frac{\gamma}{1-c}\right]$	Otherwise
Effect of supply becoming uncertain	$\downarrow Q_H$, $\uparrow Q_L$, $\uparrow Q_{Tot}$ same P_H, $\downarrow P_L$	$\uparrow Q_H$, $\downarrow Q_L$, $\downarrow Q_{Tot}$ same P_H, $\uparrow P_L$	$\downarrow Q_H$, $\uparrow Q_L$, $\uparrow Q_{Tot}$ same P_H, $\downarrow P_L$
Excess Inventory?	Yes (of Product L when both products are delivered)	No	No
$Q'_L(\rho)$	–	+	–
$Q'_H(\rho)$	0	–	+
$Q'_{Total}(\rho)$	–	+	–
$P'_{Lf}(\rho)$	0	–	+
$P'_{Ln}(\rho)$	+	–	+
$P'_{Hf}(\rho)$	0	0	0

where $F^{'}(\rho)$ denotes the sign of the derivative of $F^{*}(.)$ w.r.t. ρ and $\gamma < \delta$ is assumed.



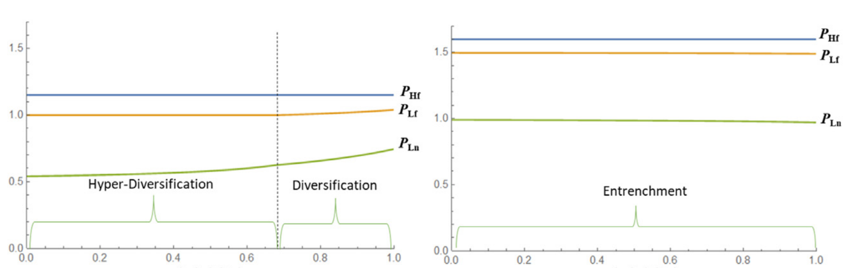
(a) $\delta = 0.7, \gamma = 0.1$ (b) $c = 0.6, \gamma = 0.1$

Fig. 2. Optimal Selling Strategy.



(a) low cost ($c = 0.08$) (b) high cost ($c = 0.98$)

Fig. 3. Optimal Order Quantities ($\delta = 0.2$, $\gamma = 0.02$).



(a) low cost ($c = 0.08$) (b) high cost ($c = 0.98$)

Fig. 4. Optimal Prices ($\delta = 0.2$, $\gamma = 0.02$).

Consumer surplus

We now consider how supplier reliability and the retailer's selling strategy impact consumers. If prices and order quantities were held constant, supply uncertainty would clearly undermine consumer surplus (CS) because supply disruptions prevent sales from occurring – sales which generate non-negative surplus for consumers. However, Section 3.2 demonstrates that prices and order quantities do vary with the probability of a supply disruption. In this section, we consider how a decrease in supplier reliability affects CS considering that the retailer utilizes the prices and order quantities that maximize its own expected profit. Proposition 2 summarizes our results.

Proposition 2 (Consumer Surplus) *Consumer surplus may increase with the probability of a supply disruption.*

While a reduction in the reliability of a supplier negatively impacts the retailer, the effect on consumers, as measured by expected consumer surplus, is less clear. In particular, we find that CS can either rise or fall with supplier reliability. Supply disruptions have a clear negative effect on consumers – some consumers will not be able to purchase their preferred item and thus obtain zero net surplus rather than some positive value. As suppliers become less reliable, consumers are more likely to encounter stockouts and the accompanying loss of surplus. Furthermore, under the Entrenchment strategy, the retailer responds to supply uncertainty by ordering fewer units and charging higher prices. Thus, consumers are worse off even when a supply disruption does not actually occur. However, under Diversification, lower levels of reliability induce the retailer to order more units of Product L and charge lower prices for this product. Lower prices imply that consumers benefit more from each transaction and higher orders imply that a greater number of transactions occur. Thus, the amount of consumer surplus generated from sales of Product L clearly increases as Supplier H becomes less reliable. In contrast, an increase in the probability of a supply disruption of Product H induces the retailer to order fewer units of this product while maintaining the same price. Thus, as Supplier H becomes less reliable, consumer surplus generated from sales of Product H clearly declines due to fewer sales when the product is successfully delivered and no sales when a supply disruption occurs. Proposition 2 indicates that it is possible for the positive effect for Product L to outweigh the negative one that arises for Product H.[4]

Fig. 5 provides two numerical examples to help explain the net impact on CS of these countervailing effects. This figure uses the parameter values of $\delta = 0.2$ and $\gamma = 0.02$ and shows how CS varies with the reliably of Product H for two different cost parameters. In both panels, we observe that CS is increasing in ρ for both low and very high levels of reliability. However, for both examples, there is an intermediary range ($0.61 < \rho < 0.94$ in.(a) and $0.66 < \rho < 0.89$ in.(b)) in which CS decreases in ρ. In these regions, consistent with the intuition given above, the reduction in the prices of Product L that results from lower supplier reliability is sufficient to induce a net positive benefit for consumers. Notice that the region in which consumers benefit from supply disruptions shrinks as costs increase. In fact, when costs are sufficiently large, CS will be strictly increasing in ρ for all levels of supplier reliability. The benefit of supply disruptions hinges on the retailer ordering significantly more units of Product L. If costs are sufficiently large, the retailer will not substantially increase its order quantity in response to unreliable supply.

Although Fig. 5 illustrates that consumers may benefit from supply disruption risk, this risk negatively affects the retailer. In extensive numerical calculations, we observe that a reduction in supplier reliability typically decreases the retailer's profit more than it increases CS. However, we do find counter examples to this result. For instance, using the parameter values $\delta = 0.02$ and $\gamma = 0.01$, Fig. 6 illustrates profit and CS as a function of Supplier H's reliability for $c = 0.1$ and $c = 0.15$. These examples provide additional support for Proposition 2. Specifically, there are levels of reliability (namely, $\rho > 0.86$ in.(a) and $\rho > 0.87$ in.(b)) for which CS is decreasing in ρ. Furthermore, for both cost parameters, the total value of CS and profit is decreasing in ρ when $\rho > 0.96$. This finding that supply disruptions can benefit consumers more than they hurt the retailer suggests that the potential benefit to consumers from supply disruption risk can be relatively large.

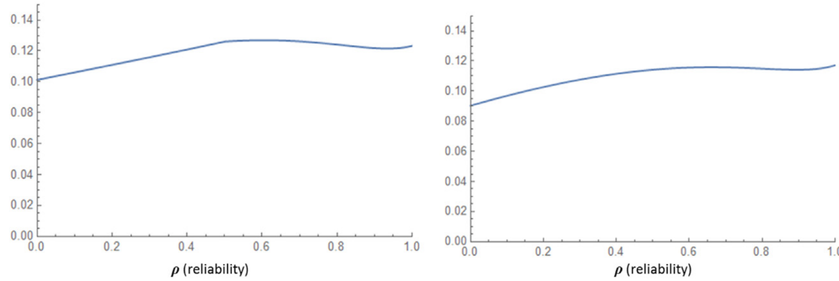
Unreliable supplier of product L

In our focal model, we assumed that Product L was always delivered but Product H may experience a supply disruption. In this section, we consider an alternate setting in which the supplier of the lower-quality product is unreliable whereas Supplier H is perfectly reliable. Such an assumption may reflect a setting in which lower-quality products are manufactured by using surplus materials (which fluctuate in availability) and/or utilize a lower cost labor force that is more distant from the retailer and thus more susceptible to transportation disruptions and have less management oversight. Specifically, we now assume Supplier H is perfectly reliable, whereas Supplier L delivers the full order quantity (Q_L) with probability ρ and delivers nothing with probability $1 - \rho$. In the absence of a supply disruption, the demand for each product continues to be characterized by Eq.s (1) and (2). However, if Product L is not available for sale, demand for Product H is:

$$D_{Hn}(P_{Hn}) = 1 - \frac{P_{Hn}}{1+\delta} \tag{13}$$

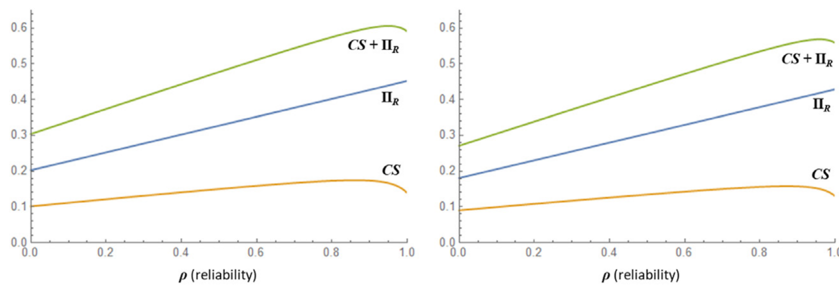
Eq. (13) is very similar to Eq. (3), except that the term $(1+\delta)$ is added to the denominator of the second term. As in the focal model, a price of zero results in full market coverage ($D_{Hn}(0) = 1$). Furthermore, a larger quality difference increases demand for the higher-quality product, i.e., $\frac{\partial D_{Hn}(P_{Hn})}{\partial \delta} > 0$. In the Web Appendix, Lemma 2 provides the optimal prices and order quantities when Supplier L is unreliable. Proposition 3 summarizes our results from this analysis.

[4] Under the Hyper-Diversification strategy, consumers also benefit from the lower prices of Product L. However, this benefit is diminished because the retailer opts not to sell all of the units that it has procured in the event that there is a supply disruption. As a result, CS is always increasing in ρ when the retailer adopts Hyper-Diversification.



(a) $c = 0.1$ (b) $c = 0.15$

Fig. 5. Consumer Surplus ($\delta = 0.2$, $\gamma = 0.02$).



(a) $c = 0.1$ (b) $c = 0.15$

Fig. 6. Consumer Surplus and Retailer's Profit ($\delta = 0.02$, $\gamma = 0.01$).

Proposition 3 (Unreliable Delivery of the Lower-Quality Product) *When the lower-quality product is unreliably supplied,*

(a) *The retailer reduces the price for the higher-quality product when a supply disruption occurs.*
(b) *The optimal response to the possibility of a supply disruption is to either:*
    order fewer units of the lower-quality product and more units of the higher-quality one; Or,
    order more units of the lower-quality product and fewer units of the higher-quality one
(c) *It is possible for consumer surplus to increase with the probability of a supply disruption.*

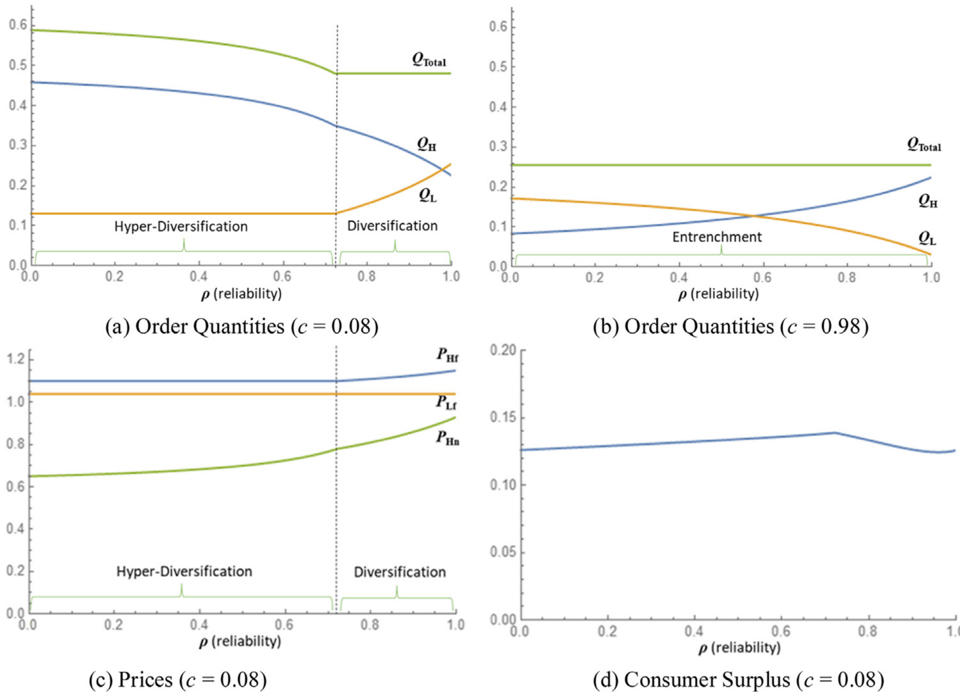
Proposition 3 indicates that the key results from our focal model continue to hold when Product L rather than Product H is the one that suffers from potential supply disruptions.[5] Specifically, Diversification, Hyper-Diversification, and Entrenchment remain potentially optimal strategies (under similar conditions to those for the focal model) and consumers can benefit from supply uncertainty. Due to the similarities in the analysis and results, we defer the technical details to the Web Appendix. However, there is one interesting difference in results that is worth noting. We observe that, when Product L is unreliably supplied, CS can increase with the probability of a supply disruption when the retailer adopts Hyper-Diversification in addition to when the retailer adopts Diversification. This expansion of the scope for which supply disruptions benefit consumers arises because supply disruptions now have the added benefit of getting consumers to consume a higher quality product.

In Fig. 7, we provide several graphs to illustrate how order quantities, prices, and consumer surplus vary with the reliability of Supplier L. This figure uses the parameter values of $\delta = 0.2$ and $\gamma = 0.02$. Fig. 7(a) shows that for low costs ($c = 0.08$), as supply disruptions become more likely (ρ decreases), the retailer orders more units from the reliable supplier (H) and fewer units from the less reliable one (L). When Supplier L is sufficiently reliable ($\rho > 0.72$), the Diversification strategy is adopted, in which the retailer prices such that all units will be sold. However, if supply disruptions are sufficiently low ($\rho < 0.72$), the retailer allows some units of Product H to go unsold when Supplier L successfully delivers the ordered quantity. This potential of acquiring excess inventory corresponds to the Hyper-Diversification strategy. Fig. 7(b) shows that for high costs ($c = 0.98$), the retailer adopts the Entrenchment strategy. Under this strategy, as supply disruptions become more likely (ρ decreases), the retailer orders fewer units from the reliable supplier (H) and more units from the less reliable one (L). Fig. 7(d), drawn assuming $c = 0.08$, demonstrates that it is possible for consumers to be better off when there is supply uncertainty. Specifically, in the region $0.72 < \rho < 0.96$, CS is decreasing in ρ.

Alternative Market structures

In our focal model, we assumed the retailer was a monopolist who sells vertically differentiated products. In this section, we modify our model to account for alternative market structures. First, we consider how the results change if the retailer sells products that are horizontally differentiated rather than vertically

[5] In Proposition 5L of the Web Appendix, we show that all three parts of Proposition 3 continue to hold in the presence of competitive pressure, i.e., the retailer, rather than being a monopolist, operates in a competitive market.



(a) Order Quantities ($c = 0.08$) (b) Order Quantities ($c = 0.98$)

(c) Prices ($c = 0.08$) (d) Consumer Surplus ($c = 0.08$)

Fig. 7. Outcomes when Supplier L is Unreliable ($\delta = 0.2$, $\gamma = 0.02$).

differentiated. Second, we examine the effects of incorporating competition into the model. These analyses enable us to obtain additional insights about the impact of supply disruption risk on retailer behavior.

Horizontal differentiation

Our focal model assumes that the retailer's two products are vertically differentiated. While many retailers offer product lines that contain products that differ in quality, another key difference across products is that they may appeal to consumers who differ in their tastes along some horizontal dimension. Thus, we now consider how a retailer can optimally respond to potential supply disruptions when its products are horizontally differentiated. Specifically, we revise the focal model so that when both products (A, B) are available for sale (at prices P_{Af} and P_{Bf}), demand is given by:

$$D_{Af}\left(P_{Af}, P_{Bf}\right) = \frac{1}{2}\left[1 - P_{Af} + \theta\left(P_{Bf} - P_{Af}\right)\right] \quad (14)$$

$$D_{Bf}\left(P_{Af}, P_{Bf}\right) = \frac{1}{2}\left[1 - P_{Bf} + \theta\left(P_{Af} - P_{Bf}\right)\right] \quad (15)$$

In this model, which is based on Sayman, Hoch and Raju (2002), θ is a measure of product substitution. A larger value of θ implies that the two products engage in greater competition for customers. We assume $\theta > 0$ so that the two products are substitutes. In order to maintain consistency with the focal model, Eq.s (14) and (15) are constructed so that prices of zero result in a total demand of one, i.e., $D_{Af}(0, 0) + D_{Bf}(0, 0) = 1$. Thus, the market is not fully covered when prices are positive.

Without loss of generality, we assume that Product A is the one that potentially experiences a supply disruption. This implies that the acquisition cost from the perfectly reliable supplier ($c + \gamma$) is higher than the acquisition cost from the unreliable supplier (c). Note that a supplier must typically make additional investments (such as in redundant systems and in accumulating larger reserves of raw materials and other inputs) in order to improve its ability to deliver orders on time. Furthermore, retailers prefer to procure products from more reliable suppliers. Thus, it is intuitive that a more reliable supplier would set a higher wholesale price than a less reliable one. In fact, we find that the retailer would not purchase any units from the unreliable supplier if it could obtain the more reliable product at a lower cost. Additionally, we impose the condition $\gamma < (1-c)/(1+\theta)$ to ensure that Supplier A's cost-advantage is not so large that it dissuades the retailer from carrying Product B.

If only Product B is available, the demand for Product B is:

$$D_{Bn}(P_{Bn}) = 1 - P_{Bn} \quad (16)$$

Notice that this is the same demand function as used in the focal model (which is intuitive because the type of product differentiation is irrelevant if the retailer is selling a single product).

The solution approach for this modeling extension is very similar to that of the focal model. Lemma 3 of the Web Appendix reports the optimal prices and order quantities when the products are horizontally differentiated. Proposition 4 summarizes the key insights obtained from our analysis.

Proposition 4 (Horizontal Differentiation) *When the retailer offers two horizontally differentiated products and the lower-cost product is supplied in an unreliable fashion,*

(a) *When a supply disruption occurs, the retailer increases the price charged for the substitute product.*

(b) *The optimal response to the possibility of a supply disruption is to order fewer units from the unreliable seller and more units from the reliable one.*
(c) *It is possible for consumer surplus to increase with the probability of a supply disruption.*

Proposition 4 confirms that many of the insights obtained in our focal model remain valid when the retailer sells horizontally differentiated products instead of vertically differentiated ones.[6] Specifically, in order to address supply uncertainty, both Diversification and Hyper-Diversification remain viable strategies for the retailer. Furthermore, because of the lower prices and higher total order quantities, supply disruptions can potentially enhance consumer welfare (as was the case in the focal model).

Despite the similarities between the models with horizontally and vertically differentiated products, there are several important differences. First, Entrenchment is no longer a viable strategy when products are horizontally differentiated. We still find that a retailer may benefit from retreating from the market when facing supply uncertainty by decreasing the total number of units ordered. However, when the unreliable product does not have a quality advantage, retreat never involves consolidating around the unreliable product. Instead, the retailer focuses upon selling the product from the reliable supplier, sometimes going as far as eliminating the unreliable supplier's product from its product mix. Second, Proposition 4(a) indicates that, when a supply disruption for one product occurs, the retailer increases the price of the other product. This is opposite to what happens when products are vertically differentiated (see Proposition 1(a)). Because horizontally differentiated products compete for similar customers (as opposed to vertically differentiated products which target different consumers types), the retailer can sell the same amount of Product B at higher prices when Product A experiences a supply disruption and thus consumers do not have the option to purchase a substitute product.

In Fig. 8, we provide two examples to illustrate how order quantities and prices vary with the reliability of Supplier A. In Example #1, for which $c = 0.6$, $\gamma = 0.1$, and $\theta = 1$, it is optimal for the retailer to adopt the Diversification strategy for all levels of reliability. Here, the products are close substitutes and have relatively high unit costs. As supply disruptions of Product A become more likely, the retailer orders fewer units of Product A and increases its price in order to stimulate more demand for Product B. Example #2 uses the parameter values of $c = 0.2$, $\gamma = 0.2$, and $\theta = 0.1$. Since unit costs are relatively small (and thus profit margins are high), as shown in Fig. 8(c), Hyper-Diversification now arises as a potentially optimal selling strategy. Furthermore, this graph shows that the retailer opts not to order any units from the unreliable supplier when this supplier is sufficiently unreliable (< 0.11). The intuition for this finding is as follows. Because the products are not close substitutes, the retailer cannot use the price of Product A to stimulate demand for Product B significantly, thus reducing the value of including Product A in the product mix.

Proposition 4(c) indicates that, for horizontally differentiated products, it remains possible for consumers to be better off when there is supply uncertainty. For instance, as demonstrated in Figure A3 of the Web Appendix, consumer surplus is decreasing in ρ for all $\rho < 0.5$ in Example #1 and within the region $0.11 < \rho < 0.18$ for Example #2.

Retail competition

Thus far, we have assumed that the retailer operates as a monopolist. We now consider a model in which the retailer faces competitive pressure. Specifically, we return to setting of vertically differentiated products, but now allow a proportion (λ) of the market to be served by competition, where $0 \leq \lambda < 1$. In this revised model, the focal retailer faces the following demands if both suppliers deliver their orders:

$$D_{cHf}\left(P_{cHf}, P_{cLf}\right) = \frac{1}{2}\left(1 - \lambda - \frac{P_{cHf} - P_{cLf}}{\delta}\right) \quad (17)$$

$$D_{cLf}\left(P_{cHf}, P_{cLf}\right) = \frac{1}{2}\left(1 - \lambda - P_{cLf} + \frac{P_{cHf} - P_{cLf}}{\delta}\right) \quad (18)$$

If, due to a supply disruption, only Product L is available, the demand for Product L is:

$$D_{cLn}\left(P_{cLn}\right) = 1 - \lambda - P_{cLn} \quad (19)$$

Under this revised model, λ is a measure of the competition intensity, where a higher value of λ indicates the focal retailer faces stiffer competition. The retailer's expected profit is:

$$\Pi_c\left(Q_H, Q_L\right) = \rho\pi^*_{cf}\left(Q_H, Q_L\right) + (1 - \rho)\pi^*_{cn}\left(Q_L\right) \quad (20)$$

where $\pi^*_{cf}(Q_H, Q_L)$ is the optimal profit in the event that there is no disruption in the supply of product H and $\pi^*_{cn}(Q_L)$ is the optimal profit in the outcome in which the supply of product H is disrupted.

To facilitate comparison with our base model which assumes it is optimal to sell both products, we restrict attention in this revised model to the setting in which $c < 1 - \lambda$ and $\gamma < \delta(1 - \lambda)$.

Proposition 5 summarizes the results from our analysis.

Proposition 5 (Competition)

(a) *The retailer reduces the price for the lower-quality product when a supply disruption occurs.*
(b) *The optimal response to the possibility of a supply disruption is to either:*
   1. *order fewer units of the higher-quality product and more units of the lower-quality product, so that the total number of units (across both products) increases; Or,*
   2. *order more units of the higher-quality product and fewer units of the lower-quality product, so that the total number of units (across both products) decreases.*
(c) *At higher levels of competition,*

[6] In Proposition 5A of the Web Appendix, we show that all three parts of Proposition 4 continue to hold in the presence of competitive pressure, i.e., the retailer, rather than being a monopolist, operates in a competitive market.

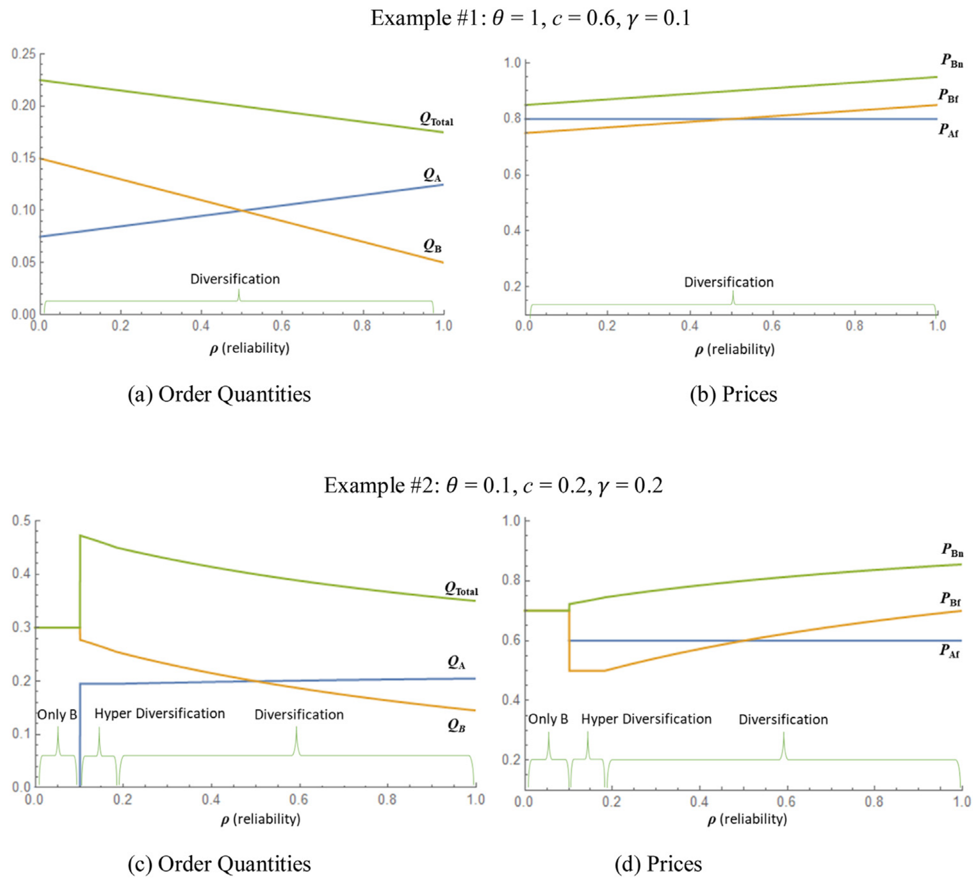


Fig. 8. Outcomes for Horizontally Differentiated Products when Supplier A is Unreliable.

The retailer orders fewer units of each product and charges a lower price at a given level of inventory. The Hyper-Diversification strategy is less likely to be the optimal strategy.

(d) *Consumer surplus (from sales by the focal retailer) may increase in the probability of a supply disruption.*

Proposition 5 indicates that our main insights of the paper remain valid in the presence of competition.[7] Specifically, when the focal retailer faces competitive pressure, the results of Proposition 1 continue to hold, namely, the retailer will lower the price of Product L when Supplier H experiences a supply disruption and all three procurement strategies (Diversification, Hyper-Diversification, and Entrenchment) remain potentially optimal. Furthermore, Proposition 5(d) replicates Proposition 2, indicating that consumers may benefit from supply uncertainty even when there is competition.

Proposition 5(c) conveys new insights regarding how competition affects a retailer's optimal response to supply disruption risk. Intuitively, as competitive pressure increases, the focal retailer has fewer potential consumers and thus orders less inventory. Furthermore, holding its inventory constant, the focal retailer must lower its prices in order to sell this inventory. Interestingly, this shift in demand implies that, as competition intensifies, the retailer has less incentive to adopt the Hyper-Diversification strategy. Instead, the retailer is likely to switch to the Diversification strategy, which involves ordering less inventory.

Extensions on supply disruptions' implications

In our focal model, we made a number of simplifying assumptions in order to ensure tractability and enhance clarity in the presentation of the results. In this section, we explore several extensions in order to test the robustness of our key results and to develop additional insights. In particular, we consider how the following implications of supply disruptions affect the retailer's strategy for addressing supply uncertainty: (1) penalties paid by the suppliers to the retailer for failed delivery; and (2) supply disruptions resulting in partial delivery of the ordered quantity.

[7] In Proposition 5L of the Web Appendix, we show that the key results in Proposition 5 continue to hold if the lower-quality product (rather than the higher-quality product) is unreliably supplied. Specifically, a supply disruption induces the retailer to reduce the price of the other product, all three procurement strategies remain potentially optimal, greater competition affects order quantities, prices, and the optimal procurement strategy in the directions outlined in Proposition 5(c), and a larger probability of a supply disruption can lead to higher consumer surplus. Proposition 5A of the Web Appendix demonstrates these key findings also hold when the two products are horizontally differentiated (rather than vertically differentiated), except that only Diversification and Hyper-Diversification are viable strategies, which is consistent with the results for the original model of horizontal differentiation (given in Proposition 4).

For each of these extensions, we build from our focal model of vertically differentiated products in which Supplier L is perfectly reliable but Supplier H may experience a supply disruption.

Penalty for delivery failures

In our focal model, we assume that, whenever a supply disruption occurred, the only penalty to the supplier is that it has to refund the retailer's original purchase. However, in practice, retailers and suppliers may have contracts that specify an additional penalty when one party fails to meet its obligations. To model such an interaction, we now assume that, in the event of a supply disruption, the retailer receives a payment of r for each unit that goes undelivered. We also assume $r < \frac{\rho}{1-\rho}(c+\gamma)$ in order to focus on the realistic situation that the penalty fee is not so high that it induces the retailer to increase its order unboundedly to benefit from these fees. When penalty fees are added to the model, the retailer's objective function in (12) now becomes:

$$\Pi(Q_H, Q_L) = \rho\pi_f^*(Q_H, Q_L) + (1-\rho)\left[\pi_n^*(Q_L) + rQ_H\right] \quad (21)$$

Notice that this revision of the objective function will not affect Stage III decisions, i.e., the optimal pricing strategy for any given (Q_H, Q_L) will remain unchanged. However, the introduction of a penalty (rQ_H) does alter the Stage I decisions. Specifically, the retailer now has a greater incentive to invest in Q_H. Proposition 6 summarizes our key results regarding how a penalty for delivery failures affects the retailer's optimal strategy for addressing supply uncertainty.

Proposition 6 (Penalties for Failed Delivery) *If the retailer receives a payment r for each unit of the higher-quality product that it orders but does not receive, Hyper-Diversification becomes more likely to be the optimal strategy. Furthermore, the order amount of the higher-quality product is increasing in r and the order amount of the lower-quality product is (weakly) decreasing in r for each of the three strategies.*

Proposition 6 indicates that the presence of a penalty for failed delivery can alter the strategy that will optimally address supply uncertainty.[8] Specifically, the retailer becomes more likely to adopt Hyper-Diversification. Recall that, holding constant all parameters, the order amounts of both Product L and Product H are higher under the Hyper-Diversification strategy than they are under the Diversification strategy. If the retailer receives a payment for each undelivered unit, the retailer clearly receives more revenue from penalty fees when it orders more units. Thus, the retailer becomes more likely to adopt Hyper-Diversification, which involves higher order quantities and thus more revenue from penalties.

Furthermore, Proposition 6 shows that penalties for failed delivery also affect how each of the selling strategies is implemented. Specifically, penalties for non-delivery create an incentive to order more units of Product H than it would have if no penalties were assessed for non-delivery. Because the products are substitutes, an increase in the order quantity of Product H encourages the retailer to order fewer units of Product L (relative to the order quantity if Supplier H did not pay a penalty for non-delivery).[9] Thus, it is interesting to see that the perfectly reliable supplier will suffer from fewer sales when the unreliable supplier is penalized for supply disruptions. Intriguingly, this result indicates that a supplier would prefer that its rival not be punished for delivery failures.

Partial delivery

Thus far, we have assumed that there are only two possible supply realizations for Product H, namely that either the entire order is delivered (with probability ρ) or no units are delivered (with probability $1-\rho$). However, in practice, partial shipments may occur. In this section, we consider a modeling extension that allows for an intermediate supply realization. Specifically, we continue to assume the retailer receives Q_H units with probability ρ, but now allow a supply disruption to result in either a partial shipment, namely $\alpha\ Q_H$ units received with probability $\rho\ (1-\rho)$ where $0 < \alpha < 1$, or no shipment, namely no units received with probability $(1-\rho)^2$. Notice that the main model of the paper is a subcase of this alternative model in which $\alpha = 0$. Furthermore, the probabilities associated with partial shipments and no shipments are parametrized to keep the model as simple as possible, but also to reflect the intuition that as a supplier becomes more reliable (i.e., ρ increases), a partial shipment becomes relatively more likely than no shipment when the supplier encounters a production or distribution challenge. All other assumptions remain the same as for the focal model. Proposition 7 summarizes the key insights from our analysis.

Proposition 7 (Partial Delivery) *When a supply disruption can lead to either partial delivery or no delivery at all,*

(a) *The retailer (weakly) increases the price of both products when a partial shipment occurs relative to prices when there is not a supply disruption.*
(b) *Diversification, Hyper-Diversification and Entrenchment remain potential optimal strategies for addressing supply disruption risk.*
(c) *Consumer surplus may increase when the probability of a supply disruption increases.*

Proposition 7(a) reports how the retailer should adjust the price of each product when a supply disruption results in a partial shipment of Product H.[10] When there is partial delivery of

8 In Propositions 6L and 6A of the Web Appendix, respectively, we show that the results in Proposition 6 continue to hold if Supplier L (rather than Supplier H) is unreliable and when the products are horizontally differentiated (rather than vertically differentiated). In both alternative models, Hyper-Diversification becomes more likely when there is a penalty for failed delivery, the order amount of the reliably supplied product increases in r, and the order amount of the unreliably supplied product decreases in r. These additional results require that $r < \rho c/(1-\rho)$, which is slightly more restrictive than the condition specified in the text for the focal model.

9 Under Entrenchment and Diversification, the order amount of Product L is strictly decreasing in r. Under Hyper-Diversification, the order amount of Product L is independent of r.

10 In Proposition 7L of the Web Appendix, we show that the key results in Proposition 7 continue to hold if the lower-quality product (rather than the

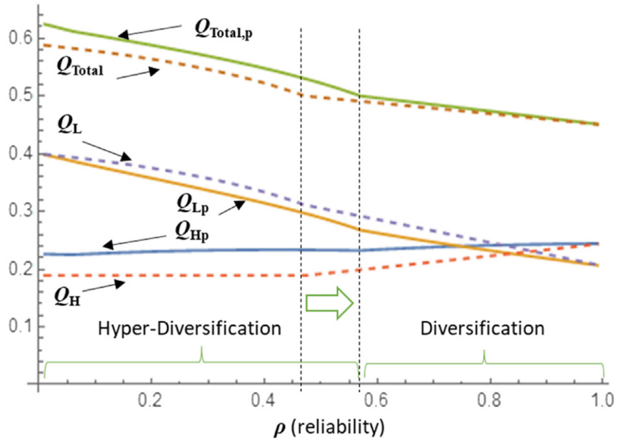


Fig. 9. Effect of Partial Delivery on Optimal Order Quantities ($\delta = 0.9$, $c = 0.2$, $\gamma = 0.02$, $\alpha = 0.5$).

Product H, the retailer now has fewer units of this product available to sell and sets a higher price to clear this limited inventory. Because a higher price of Product H relaxes competition with Product L, the retailer can increase the price of Product L and still maintain the same amount of sales.

Parts (b) and (c) of Proposition 7 indicate that our key findings from the focal model still hold when we allow for the possibility of partial delivery. In particular, there are market parameters for which each of the previously identified strategies is the retailer's optimal response to the possibility of a supply disruption. Furthermore, we find that consumers can benefit from a supplier becoming less reliable.

Through extensive numerical analysis, we also identify some interesting ways that partial delivery influences the order amounts under each strategy and the regions for which each strategy is optimal. Fig. 9 illustrates several of our key insights, using an example in which $\delta = 0.9$, $c = 0.2$, $\gamma = 0.02$, and $\alpha = 0.5$. It shows that Hyper-Diversification may become a more prevailing optimal strategy for addressing supply uncertainty when supply disruptions can result in partial delivery (as opposed to always resulting in no units being shipped). Recall from the focal model that, all else equal, the order amounts of both Product L and Product H under Hyper-Diversification exceed those under Diversification. Thus, when the retailer receives a partial delivery of Product H, adoption of the Hyper-Diversification strategy enables the retailer to receive more units of this product, thereby generating more profit (compared to the outcome under Diversification). This advantage expands the region of parameters for which Hyper-Diversification is optimal.

higher-quality product) is unreliably supplied. Specifically, a partial shipment induces the retailer to increase the prices of both products, all three procurement strategies remain potentially optimal, and a larger probability of a supply disruption can lead to higher consumer surplus. Proposition 7A of the Web Appending demonstrates these key findings also hold when the two products are horizontally differentiated (rather than vertically-differentiated), except that only Diversification and Hyper-Diversification are viable strategies, which is consistent with the results for the original model of horizontal differentiation (given in Proposition 4).

Furthermore, Fig. 9 shows that, under both Diversification and Hyper-Diversification, the retailer orders more (fewer) units of Product H (Product L) when a supply disruption can result in partial delivery, rather than always leading to no units being received. The retailer orders more units of Product H so that the scarcity of Product H will not be as severe. In turn, due to the two products being partial substitutes, the retailer orders fewer units of Product L.

Concluding remarks

Managerial implications

Supply disruptions are becoming relatively common and have a variety of potential causes including pandemics, power outages, terrorist attacks, labor strikes, transportation delays, temporary unavailability of an input, system bottlenecks, adverse weather conditions, telecommunication outages, fires, unplanned production downtimes, cyber crime, political unrest, changes in government regulations, manager errors, and miscommunications. Our paper provides important insights for retailers as they attempt to identify the appropriate procurement and pricing strategies for dealing with an unreliable supplier. An overarching theme is that retailers need to develop integrative strategies that coordinate decisions across suppliers, i.e., one can mitigate the negative effects of unreliability of one supplier by altering how much it orders of another supplier's product and how it prices this product. We identify three potentially viable strategies: Diversification, Hyper-Diversification, and Entrenchment. By procuring more inventory from a more reliable supplier and less from an unreliable one, Diversification mitigates the effects of potential supply disruptions by reducing the retailer's dependence on an unreliable supplier. Hyper-Diversification addresses supply risk by placing large order quantities, thus enabling the retailer to maintain high sales even if a supply disruption occurs. Entrenchment involves consolidating one's strategy around the unreliable supplier's product. In choosing which strategy to adopt, the retailer should account for the probability of supply disruptions, relative costs and quality, consumers' degree of price- and quality-sensitivity, compensation received for failed delivery, and competitive factors.

Our paper provides several key managerial insights. First, we demonstrate that a retailer can mitigate the negative impact of supply uncertainty by adjusting order quantities *before* a supply disruption occurs. Within the operations management literature, much attention is paid to the prevention of production shortfalls, e.g., quality controls to limit scrap and dual sourcing to insure availability of necessary inputs. The focus is typically upon the producers' decisions. For instance, a working paper by Kim and Morton (2015) considers capacity decisions by a manufacturer in light of potential supply disruptions. Namely, a manufacturer may invest in excess capacity in order to fulfill large orders that occur whenever a rival manufacturer experiences a supply disruption. Our research complements such research by taking the perspective of the retailer rather than of the manufacturer.

Second, we find that, in a multi-product environment, when one product becomes less reliable, a retailer needs to adjust not only the prices and inventory orders for that product, but also for potential substitute products. Typically, if one supplier becomes less reliable, a retailer should increase total order quantities and order relatively more units of a substitute product (regardless of whether that alternative product has a superior or inferior quality). It is optimal to acquire inventory that may end up going unsold, i.e., adopt Hyper-Diversification, if unit costs are low and/or the products have substantially different qualities. Such a strategy is particularly attractive when a supplier must pay a penalty if it fails to deliver the ordered quantity and/or if supply disruptions may result in a portion of the order being shipped (rather than no shipment at all). However, there are circumstances in which a retailer should decrease total order quantities but order more units from the unreliable supplier. Such an Entrenchment strategy is optimal when unit costs are relatively high and there is a modest quality difference between the products. For instance, in the market for retro video game consoles, Nintendo was repeatedly unable to fulfill retailers' orders for its NES Classic Edition, with some consumers going so far as to speculate that the manufacturer was intentionally keeping its supply from meeting demand (Novet 2017). Our results suggest that retailers may benefit from increasing emphasis on selling the NES Classic Edition. Indeed, GameStop continued to advertise and increase orders of this console despite frequent stockouts (Grugg 2016). Perhaps, emphasizing this product procured from an unreliable supplier waswas an advantageous strategy for drawing consumers into their stores, while at the same time GameStop could offered a less popular alternative, such as the Atari Flashback, to customers who encountered stockouts of the more preferred product.

Third, we provide guidance about how prices should be adjusted when there is a delivery failure. We find that the appropriate response to a supply disruption critically depends upon whether the stocked-out product has the same quality as the retailer's other product offerings. When a retailer's product mix contains products that differ in quality, the retailer should decrease the price of the in-stock product when another product stocks out. This implies, counterintuitively, that it is optimal to charge higher prices when realized supply is high rather than low. In contrast, when products vary on a personal taste dimension and a product stocks out, the retailer should increase the price of the remaining products. Furthermore, if a supply disruption results in only a fraction of the full order being delivered, the retailer should increase the price of all products relative to the price charged when there are complete shipments.

These results could also apply when stockouts arise for reasons other than supply disruptions. For example, spikes in demand during the early stages of the COVID-19 pandemic caused many products to stock out. However, several other products, such as Pretzel Pop Tarts, chocolate hummus, Barilla's red lentil penne pasta, Progresso chicken corn chowder, Honey Nut Cheerios, Banzai spaghetti made from chickpeas, Morton Lite salt, CORE water, and plant-based meats, remained in ample supply (Argento 2020, Mak 2020). Given consumers' increased willingness to try new brands and products during this time (Garcia 2020), one might have expected retailers to reduce the prices of the products with large inventories in order to induce more switching behavior. However, we did not observe such price cuts. This behavior is consistent with our finding that a retailer should price relatively high when products differ primarily on a horizontal dimension. In particular, pretzel-flavored Pop Tarts differ from other flavors of Pop Tarts on a taste-dimension rather than being of a lower or higher quality. Likewise, red lentil pasta, chicken corn chowder, and Honey Nut Cheerios have similar quality to other varieties of the same brand (which have stocked out) but are targeted towards consumers who have different tastes.

Fourth, our results have important implications for retailers' strategic management of store brands. Over the last few decades, market share for store brands (also known as private labels) has been growing very rapidly, especially in the grocery category (Sethuraman and Gielens 2014). Sethuraman (2009) identifies a number of important topics for future research in this area, including the need to examine market characteristics that influence the prices of store brands relative to national brands. Our paper considers a market factor, namely supply uncertainty, that has not been explored previously in the context of private brands. Private (national) brands would correspond to the lower-quality (higher-quality) product in our model. Consistent with Sethuraman (1995), we assume the cross-price effects of national brands and private labels are symmetric. Our findings indicate that a retailer can use the private label as a buffer against uncertain delivery of the national label, or vice-versa. It is critical for retailers to evaluate which type of product is more likely to experience a supply disruption. If a retailer is utilizing a relatively unreliable supplier of a national brand, then it may want to increase the order amount of its private label and reduce the price of this product to mitigate supply uncertainty. In contrast, if a retailer cannot reliably produce its private brand, it may need to reduce the price margins on the national brands and order more units of these brands.

Overall, a majority of our findings are highly consistent with the literature on private labels. For example, we find that a retailer can use small differences in prices to increase demand for the private brand, which is a finding that has strong support within the extant literature (Sethuraman and Gielens 2014; Sethuraman 2009). However, our results may also help explain one puzzle in the field. Specifically, Sethuraman (2009) notes that a common analytical result in the literature is that the national brand will have a low price when the store brand is a close substitute, but that this finding has low credibility among managers and very limited empirical support. In fact, there is more empirical evidence of high (rather than low) prices for national brands when there is a high degree of substitutability. In our model, a low difference in quality could induce a retailer to adopt the Entrenchment strategy (see Fig. 2(b)). Under this strategy, the retailer should set relatively high prices for both the private and national brands (see Fig. 4(b)). These results suggest that, in the presence of supply uncertainty, the retailer would set high prices for the national brand when the store brand is a relatively close substitute, thus providing theoretical support for an empirical observation that does not closely align with previous analytical models.

Fifth, we find that supply disruptions, counter-intuitively, can be a boom for consumers. Although supply disruptions prevent some consumers from being able to obtain their most preferred product, under all three strategies, the anticipation of supply disruptions leads retailers to set a lower price for one of the products. Notice that a price reduction, although implemented in an effort to induce more consumers to purchase a particular product, is also received by consumers who would be willing to pay a higher price. Thus, there are always some consumers who benefit from supply uncertainty. For example, during the COVID-19 pandemic, there were substantial concerns about possible supply disruptions, especially for premium coffee blends (Harris 2020), and demand for coffee shifted away from consumption in cafes and restaurants towards other channels such as curbside pickup and home delivery of coffee beans (Hatcher 2020, Horner 2020). Yet, online stores' prices for premium specialty coffees declined substantially. For example, the average price at the upper end of the market fell by 16.1% in April 2020, even though the average price at the lower end actually increased by 0.3% (Roberts and Bellman 2020). Such a change in prices clearly benefited consumers who strongly prefer premium coffee blends.

Furthermore, the anticipation of supply disruptions can benefit consumers by inducing the retailer to order a larger total amount of inventory (relative to the case of perfectly reliable suppliers), as occurred during the COVID-19 pandemic as some online retailers attempted to stockpile coffee beans (Harris 2020). In general, our results suggest that stores may be able to generate higher foot traffic by utilizing less reliable suppliers. Indeed, this insight is consistent with the "treasure hunt" phenomenon that stores such as Costco and the Dollar Tree employ, which involves low prices coupled with uncertain product availability (Shaw 2017). This strategy encourages frequent store visits since consumers never know what they will find in the store due to the constantly changing product offerings.

Directions for future research

The limitations of our models provide several important opportunities for future research. Although we investigate the effect of competition in a modeling extension, we view our analysis as a preliminary exploration that future research can build upon. For example, it would be useful to examine the effect of supply uncertainty in more realistic market settings, such as one in which multi-product retailers compete against each other and are all strategically choosing their prices and order quantities. Furthermore, it would be useful to incorporate parameters for the degree of own-price demand elasticity and cross-price elasticity of demand. Such a model could generate additional insights regarding how a retailer's optimal strategic response to supply disruptions depends on how effective price reductions are at acquiring new customers and at inducing consumers to switch brands.

It would also be interesting to consider the interaction of distribution channel choices and supply uncertainty, e.g., how the impact of supply disruptions differs across online vs. offline channels or across direct vs. indirect channels. In addition, it may be insightful to incorporate additional dynamics into the model. For example, retailers' decisions of which suppliers to include in their procurement networks could shape stock-out rates which, in turn, could affect store traffic. Finally, it would be useful for future research to examine empirically how pricing and procurement strategies of retailers respond to supply disruptions and the anticipation of such disruptions. A central challenge of such empirical work will be estimating retailers' perceptions about the probability of a supply disruption since such perceptions are unlikely to be publicly reported.

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.jretai.2020.11.005.

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